Split Application of Sulfur and Potassium and their Leaching Potential for Corn Grown on Irrigated Soils

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Dedication

I like to personally dedicate this thesis to Clara and Norbert Jansen. While they are not with us anymore and able to see my work, I like to think they would be proud to see my research in the field of agricultural studies.

Abstract

Irrigated coarse textured soils have the potential to produce high yielding crops but are also likely to leach out fertilizer nutrients before they can be utilized. Few studies have considered split fertilizer applications of sulfur (S) and potassium (K) on coarse textured soils. Eight fertilizer studies, four S and four K, were conducted to assess how split applications of S and K fertilizers affect plant uptake, corn grain yield, and the leaching potential over the growing season. Each site had four at planting (AP) and four in-season (IS) fertilizer rates applied for a combination of 16 different fertilizer treatments. Various plant tissue, remote sensing readings, and soil samples were taken to assess nutrient availability and movement through the soil profile. Suction cup lysimeters were used in select treatments to monitor soil pore water concentrations. Single or split applications of S and K fertilizers did not increase grain yield. Significant differences among different AP and IS rates were found for early plant and ear leaf S and K concentrations, but these were unable to predict grain yield. Normalized difference vegetation index or SPAD chlorophyll readers did not prove to be indicators of final corn grain yield in either S or K studies. Plant NDVI data was able to predict biomass in K studies. Lysimeter data from S studies suggest increased S concentration towards the end of the growing season but provided no advantage of split application of S fertilizer to avoid S losses. Lysimeter data suggested early season K movement and in most sites and IS fertilizer application had the greatest effect on end of the growing season pore water K concentration. Because of potential early K movement, split applications may be advised for farmers growing corn on coarse textured soils to avoid K losses.

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1.0 Introduction

1.1 Justification

Corn (*Zea mays* L.) response to sulfur in Minnesota has steadily increased over the past ten years (Kim et al., 2013) but the direct cause is unknown. Soils in the United States have been showing S deficiencies as a possible result of reduced atmospheric emissions of sulfur dioxide (SO_2) after the enactment of the Clean Air Act in 1971 (Scherer, 2001; Riley et al., 2002; Aulakh, 2003). Since the 1980s, U.S. air emissions of SO_2 have been reduced by 83%. Similar trends have occurred in other countries with emission reduction laws (United States Environmental Protection Agency (USEPA), 2013). Other possible factors contributing to reduced sulfate-S (SO_4^{2-}-S) in soils include higher grade fertilizers with less impurities and the reduction of fungicides and pesticides containing S (Hergert, 2000). While anthropogenic S additions to soils are important, around 95% of S in the soil is mineralized from soil organic matter (SOM) (Ghani et al., 1993; Rehm and Clapp, 2008). In coarse textured soils, SOM is often low and sulfate (SO_4^{2-}) mineralized from SOM is likely to be leached out because of the negative charge on SO_4^{2-} and high water percolation due to large pore size in coarse textured soils (Jones Jr., 2012). Since course textured soil has low water retention, soils are often irrigated. Corn grown on sandy soils in Minnesota have previously been shown to respond to S fertilizer (O'Leary and Rehm, 1990, Kaiser et al., 2011) and may need special management to ensure adequate S availability over the growing season.

Sulfur is an important secondary macro-nutrient needed for proper plant growth and development. In plants, S helps regulate the synthesis of amino acids and proteins, forms plant structure, and regulates plant metabolism (Jones Jr. et al., 1991). Guidelines exist to determine whether corn plants are considered deficient in S based on S concentration in the ear leaf at the R2 growth stage (Abendroth et al., 2011). However, the R2 growth stage it is too late to add needed nutrients if a deficiency is detected (Rehm and Schmitt, 1989). Sulfur deficiencies can affect yield in crops, thus correlation between plant uptake of S and plant yield have been studied (Rehm, 1984; O'Leary and Rehm, 1990; Pangani and Echeverria, 2011). Field studies by Pangania and Echeverria (2011) found relationships between ear leaf S and grain yield. More data on plant uptake could help create better in-season predictors for grain yield.

Sulfur guidelines for corn grown on sandy soils call for fertilizer to be broadcast and incorporated before planting (Kaiser et al., 2011). Because of the potential of SO_4^{2-} to leach, especially on sandy soils that are irrigated, splitting the application of the fertilizer may help plants optimize S uptake and increase plant yield. Split application of S fertilizer studies have been conducted on rapeseed (*Brassica napus* L.) showing increased grain yields over single S fertilizer application (Ahmad et al., 1998 and Ahmad et al., 2005). A similar study was conducted with corn but was preformed near a coal burning power plant which likely was responsible for no grain yield response (Rehm, 1993). More research on split application of S fertilizer on corn is needed to make better recommendations to farmers for the best management practices and for optimal grain yields.

Potassium (K) is a macronutrient recommended for corn production. Corn grown in Minnesota on sandy irrigated soils face potential cation leaching due to a low cation exchange capacity (CEC) resulting in the soil's inability to hold nutrients (Jones Jr., 2012). Irrigation of sandy soils can also add to the potential for nutrients, such as K, to percolate through the macropore spaces. Potassium is needed in large quantities second only to nitrogen (N) for corn production. If K is lost through leaching, it can be very costly to farmers (Frank, 2000). In addition, plants are able to accumulate K beyond the point of sufficiency which is known as luxury consumption (Jones Jr., 2011). Finding the optimal rate and application time for K fertilizers has important economic implications for farmers.

Potassium is taken up by plants in the K^+ form and is not a structural component of organic molecules. Plants use K to help regulate water, for the opening and closing of stomata, transport of carbohydrates within the plant, protein production, and may aid in disease resistance (Jones et al., 1991; Rehm and Schmitt 1997). Unlike S, K uptake in plant tissue can be used at different growth stages to serve as a predictive tool for grain yield (Clover and Mallarino, 2013).

Due to K's ability to be leached from sandy soils, split applications may be a useful management tool to avoid losses and maintain availability. A handful of studies have researched split application of K for crops such as coastal bermudagrass [*Cynodon dactylon* (L.) (Burton and Jackson, 1962)], alfalfa [*Medicago sativa* (L.) (Kresge and Younts, 1962)], and soybean [*Glycine max* (L.) Merr. (Kolar and Grewal, 1994)]. For all aforementioned crops, using split applications of K resulted in greater yields compared to a single application. These results suggest that split fertilizer applications could also increase grain yield of corn if done on K deficient soils.

Sulfur Study

1.2 Literature Review

1.2.1 Sulfur in Corn Plants

Sulfur is a secondary macro-nutrient needed by plants to develop and function properly. Sulfur is utilized in plants to regulate the synthesis of proteins, is a component of amino acids, aids with structure formation, and regulates metabolism (Jones Jr. et al., 1991). Plants uptake S in the SO_4^{2-} form (Black, 1993). Sulfur is considered an immobile nutrient in plants and physical symptoms of deficiency occurs in the youngest leaves. Typical symptoms of S deficiency include interveinal chlorosis and stunted or delayed growth (Jones Jr., 2012). Current S fertilizer guidelines for corn in Minnesota are that 28 kg S ha^{-1} should be broadcast applied and incorporated before planting on coarse textured soils (Kaiser et al., 2011).

Plant tissue tests using ear leaf samples are often used to establish if the crop has an adequate amount of available S. Ear leaf S concentration for samples collected at the R2 growth stage is considered low when < 2.0 g S kg^{-1} (Kaiser et al., 2013). Various studies have had mixed results when using S concentrations in ear leafs as a predictor of crop yield. Rehm (1984) found no correlation between ear leaf S concentration and corn grain yield. However, O'Leary and Rehm (1990) found a significant correlation between ear leaf tissue S concentrations and grain yield of corn at 6 of 10 field locations. Other studies have suggested using chlorophyll meter readings assessed by SPAD meters as a better indicator of S sufficiency and grain yield response (Pangani and Echeverria, 2011).

Plant tissue nutrient ratios are also sometimes studied for their effect on protein synthesis and plant growth. The ratio of N to S (N:S) can be used to imply the availability of nutrients for the plant's synthesis of proteins. Changes in these ratios can suggest changes in plant metabolism and thus the quality of proteins made (Friedrich and Schrader, 1978). Total N:S ratios can also be used to suggest insufficient S for protein synthesis, with insufficiency occurring around ratios of greater than 15:1 or 16:1 (Stewart and Porter, 1969; Cassel et al., 1996). Nitrogen:S ratios less than 15:1 are considered sufficient levels for proper plant growth and protein synthesis.

1.2.2 Sulfur in Soil

Sources of plant available S in the soil include mineralized SOM, weathering of soil minerals, atmospheric deposition of SO_4^{2-}, S contained in pesticides, organic waste (including manure), SO_4^{2-} in irrigation water, and fertilizer (Hergert, 2000; Scherer, 2009). Of these sources, SOM supplies soil with its largest pool of S, totaling around 95% of total S (Ghani et al., 1993; Rehm and Clapp, 2008). Sulfur obtained from minerals is found in various forms and as they are weathered can contribute to SO_4^{2-}-S in soils (Rehm and Clapp, 2008). Atmospheric deposition of SO_4^{2-} was a potential provider of S to crops, but atmospheric S inputs have decreased as a result of environmental concerns (Scherer, 2009). Industrial sources of S, such as SO_2 emissions, traditionally came from coal-burning power plants until the U.S. congress passed the Clean Air Act in 1971 (Scherer, 2001). Sulfur dioxide emissions since have been drastically reduced, decreased on average by 83% since 1980 in the US, with similar trends around the world (Riley et al., 2002; Aulakh, 2003; USEPA, 2013). Along with reductions of SO_2

emissions, there has been a decrease in the use of S containing fungicides, S containing pesticides, and the use of high grade fertilizers. As a result of these reductions, many soils around the world are now facing S deficiency (Scherer, 2009).

Soil tests are used to assess crop sufficiency. While many studies have examined the correlation between soil S and crop production, most have found no relationship between the two (Bloem et al., 2002; Pagani and Echeverria, 2011; Kim et al., 2013). The only time a soil S test is recommended is for corn grown on sandy soils (Kaiser et al., 2011). Since SO_4^{2-} is mobile in soils, it is unclear whether soil samples taken in the spring will accurately represent the sufficiency of S to the crop.

1.2.3 Sulfur Leaching

One of the main pathways of S loss in soil, besides plant uptake, is through leaching of SO_4^{2-}. Sulfur in the SO_4^{2-} form is an anion and can be leached through heavy rainfall or through the use of irrigation (Rehm and Schmitt, 1989). Sulfate adsorption rate in soils can depend on soil pH, being more strongly adsorbed at low pH levels. At pH 6.5 or greater, adsorption is considered negligible (Curtin and Syers, 1990). Sulfate leaching is usually lowest during winter as a result of reduced microbial mineralization rates (Castellano and Dick, 1990) and tends to be less in finely textured soils (Scherer, 2009). In areas prone to leaching it is suggested to apply elemental S that requires oxidation to form SO_4^{2-} or a mix of SO_4^{2-} and elemental S fertilizers to delay SO_4^{2-} leaching and maintain availability over the growing season (Scherer, 2009; Hergert, 2000). Sulfate leaching is mostly an economical concern for farmers rather than an environmental concern. Environmental concerns for S leaching are low but there are still guidelines for drinking water in the US. The USEPA has set a secondary maximum contaminant level of 250 mg L^{-1} for drinking water mostly for the aesthetic, odor, and taste qualities and has only found a few cases for health concern pertaining to diarrhea caused from elevated SO_4^{2-} concentrations in drinking water (USEPA, 1991).

1.2.4 Sulfur Requirements and Recommendation

Sandy soils with a low SOM concentration require S fertilizer to maximize grain yield (O'Leary and Rehm, 1990; Hergert, 2000; Kaiser et al., 2011; Kim et al., 2013). In S response studies, rates to maximize grain yield range between 7 kg S ha^{-1} to 28 kg S ha^{-1} depending on soil texture and tillage practices (Rehm, 1984; Rehm and Schmitt, 1989; Rehm 2005; Rehm and Clapp, 2008). Because of the vulnerability of SO_4^{2-} to leach, especially on sandy soils, field studies have been conducted to determine if S fertilizer should be split applied. Studies performed by Ahmad et al. (1998, 2005) determined that increased yields of *Brassica napus* L. could be achieved with split applications of S. An additional study focused on split application of S for corn grown on sandy soils (Rehm, 1993). This study concluded that there were advantages of split application of S fertilizer over single application. It should be noted that only one of two years of the study had a response due to S application because of the proximity of the field sites to a coal-burning power plant that possibly supplied satisfactory inputs of S. The results of this study may not be the best representation of the effects of split application of S fertilizers on corn. Further study of split application of S on corn may be beneficial, especially for sandy soils.

1.2.5 Lysimeter Use

Sulfur leaching studies have utilized various lysimeter types to assess how fertilizer type affects S leaching and to quantify how much S is lost over a growing season (McKell and Williams, 1960; Riley et al., 2002). While lysimeter studies can help estimate leaching in soils, concerns on how to best collect this data is debated. One of the first problems encountered in lysimeter studies is trying to choose a lysimeter type and installation plan. Basic suction cup lysimeters, consisting of narrow cylindrical tubes with a porous cup attached to the bottom, are most frequently used for their ease of installation (Weihermüller et al., 2007). These suction cup lysimeters can be used for short-time interval collections and give the advantages of only causing small localized disturbances of the water flow in the soil (Weihermüller et al., 2007). One disadvantage is that the lysimeters create a non-permanent flow and therefore can cause sorption of certain nutrients to the suction cup. It is suggested to discard the first sample collected because of the sorption on the ceramic cup (Weihermuller et al., 2007).

The selection of lysimeter type can be based on the type of soil where it is installed. Use of shallow filled in soil type lysimeters is discouraged because they alter the soil profile and will not give an accurate picture of what is going on in the natural soil systems (Munson and Nelson, 1963). Fill in type lysimeter types are only suggested to be used on soils that are very sandy (Munson and Nelson, 1963). The last consideration to be made in lysimeter choice and construction is assuring that materials used do not react with target nutrients or compounds being monitored. Weihermüller et al., 2007 warns against potential sorption of SO_4^{2-} onto the suction cups and has listed various materials such as stainless steel, glass, oxide ceramic, nylon, polytetrafluoroethylene (PTFE), and polyvinyl chloride (PVC) as materials with documented suitability for lysimeter construction for SO_4^{2-} sampling.

Potassium Study

1.3 Literature Review

1.3.1 Potassium in Corn Plants

Potassium is a macro-nutrient needed by plants to grow and function properly. Potassium is used to regulate water movement in plants, used for control of opening and closing stomata in leaf cells, and the movement of carbohydrates within the plant (Jones Jr. et al., 1991; Jones Jr., 2011). Other research suggests that K can help increase protein production, increase water use efficiency, and provide some resistance to disease and pests (Rehm and Schmitt, 1997). Potassium is mobile in plants. Deficiency symptoms occur in older leaves and then move into newer leaves (Frank, 2000). In corn, K deficiency often starts with the yellowing of leaf edges followed by necrosis of leaf tips and lower leaf margins, and then yellow stripping may occur (Frank, 2000; Rehm and Schmitt, 1997). Plant tissue analysis can be used to assess the sufficiency of K over a growing season, but cannot be used to predict the need for the following year’s crop (Rehm and Schmitt, 1997). Clover and Mallarino (2013) found that K concentrations in V5-V6 growth stages and at R1 were significantly correlated to yields. Plants at the V5-V6 had critical concentrations at 25 g K kg^{-1}. Ear leaf concentrations at the R1 stage had critical values of 11 g K kg^{-1} (Clover and Mallarino, 2013).

Potassium typically makes up from 10-50 g kg^{-1} of the leaf dry weight and requires approximately 15-30 g Kg^{-1} K for sufficient nutrient levels (Jones et al., 1991). Current Minnesota guidelines for ear leaf tissue concentrations in corn at R2 define corn plants as deficient when <13 g kg^{-1} and low at 13-17 g kg^{-1} (Kaiser et al., 2013). Plants obtain more K than needed for sufficient growth if soil K is very high. Luxury consumption of K occurs when concentrations are over 29 g Kg^{-1} K in corn plants (Jones Jr., 2011). Potassium needs of crops are high, second only to N. A 9.4 Mg ha^{-1} yielding corn crop will remove up to 39 kg K ha^{-1} (Frank, 2000).

1.3.2 Potassium in Soil

Potassium is an abundant nutrient in the soil and can be found in three main pools: unavailable K, slowly available/fixed, and available/exchangeable K. Most K in soils occurs in the unavailable pool which consisting of 90 to 98% of the total K (Frank, 2000). Fixed K is trapped between layers of 2:1 clays in the soil where it may slowly be released back into the soil. Potassium exists as K^+ in the soil, and is taken up by plants in this form (Jones Jr., 2011). Available pools of K in soils can be found in soil water or in soil colloids.

Soil tests for K are used to predict the potential for a crop yield response. Routine soil tests extract from the pool of K potentially available to the plant. This pool may include K in soil water solution and the exchangeable K (Rehm and Schmitt, 1997). Multiple soil factors affect the availability of K. Besides the type of parent material, factors such as soil moisture, soil oxygen concentration, soil temperature, and tillage can affect the amount of available K (Rehm and Schmitt, 1997; Frank, 2000; Munson and Nelson, 1963). Higher soil moisture reduces the length of the path needed for K to reach the plant roots, increasing availability to the plant (Mackay and Barber, 1985; Rehm and Schmitt, 1997; Frank, 2000). Unfortunately, on coarse textured soils, higher water inputs can cause K to be lost through the soil profile via percolation when water is not able to leave the field as runoff (Munson and Nelson, 1963).

Soil oxygen and aeration levels can influence plant respiration, and thus plant uptake of K. Oxygen levels will be impacted by soil moisture and aeration which can be influenced by compaction of the soil (Frank, 2000). Temperature also affects the amount of K available to plants by affecting plant metabolism (metabolic activities are lower at lower temperatures) and affecting the rate of K release from the unavailable pools (Frank, 2000).

1.3.3 Potassium Leaching

Potassium is considered an immobile nutrient in soil environments but can be lost through leaching in certain soils. Leaching activity in soils will mostly depend on the available pool of K and soil texture (Alfaro et al., 2004). Soil texture affects CEC, the soil's ability to retain cations, being greater in soils high in clay and lower in course-textured sandy soils (White, 2005). Organic matter in soil can make up large portion of a soil's CEC, especially on sandy soils. One study found that as much as 80% of CEC was found in the organic matter of fine sand soils (Spencer, 1954). Therefore, soils with course-texture and low SOM are most likely to exhibit leaching of K. According to Kolahchi and Jalali (2007), the soil matrix of sandy soils with low amounts of clay and low buffer capacity will not have a strong interaction with K^+, which will lead to high amounts of K in soil solution where it is vulnerable to leaching. The USEPA has not set any drinking water limits or standards for K, as it does not cause any major health problems or environmental problems. However, The World Health Organization has set a recommended level of 12 mg L^{-1} (WHO, 2006). Main concerns for K leaching is due to the economic standpoint of farmers investing in fertilizer that does not return a net profit.

Potassium leaching studies have utilized lysimeters to assess the movement of K fertilizer through the soil profile (Alfaro et al., 2004; Kolahchi and Jalali, 2006). Alfaro et al. (2004) found that there is an increase in K leaching at the beginning of the drainage season then a constant flow due to macropore water flow followed by matrix flow. Similar to concerns about materials used for sulfur monitoring, Weihermüller et al. (2007) cautioned the potential of clay suction cup to have CEC interactions with K in the soil solution. Stainless steel, glass, oxide ceramic, nylon, PTFE, and PVC are suitable materials for lysimeter construction for monitoring K (Weihermüller et al., 2007).

1.3.4 Potassium Requirements and Recommendations

Potassium guidelines are made for corn in Minnesota based on soil testing using the NH_4OAC-K test. Soils are considered Very Low in K when concentrations are < 40 mg K kg^{-1}, Low 40-80 mg K kg^{-1}, Medium 80-120 mg K kg^{-1}, High 120-160 mg K kg^{-1}, and Very High > 160 mg K kg^{-1} (Kaiser et al., 2011). Grain yield increases are likely when K fertilizers are applied to soils that have low soil test values (Kaiser et al., 2011). These values are general guidelines made for Minnesota soils which tend to be relatively rich in topsoil and soil nutrients, thus may not be work for atypical soils in Minnesota such as sandy soils. Rehm and Sorensen (1985) conducted K fertilization studies on sandy irrigated soils testing in the Medium soil K range, but did not find any difference in yields from K rates that ranged from 0 to 269 kg K ha^{-1}. These results suggest more research needs to be conducted on these soils to understand interactions between K fertilization and grain yield of corn grown on sandy irrigated soils.

Because of the potential for nutrients to leach out of sandy soils, split applications of fertilizer should be considered. Only a handful of studies have evaluated split application of K fertilizers but these studies have found an increase in yield in soybean (Kolar and Grewal, 1994), coastal bermudagrass (Burton and Jackson, 1962), and alfalfa (Kresge and Younts, 1962). These studies were conducted on sandy soils which suggest that research on split application of K on sandy irrigated soils could be beneficial for corn production.

1.4 Objectives

While recommendations have been made for S fertilizers for corn grown on sandy soils, more research on S management is needed. Previous work on split applications for K fertilizer has found to increase yields in various crops and thus may be beneficial to corn yield as well. The use of split applications may also help reduce leaching losses of fertilizer applied on sandy textured and irrigated fields. Information from this research could help Minnesota farmers make important crop management decisions to help them optimize yields while minimizing their fertilizer inputs. The objectives of this study are:

1) Evaluate sulfate and potassium availability from single and split applications of fertilizer on irrigated corn.
2) Assess the ability of remote sensing tools to detect deficiencies in sulfate and potassium.
3) Determine the potential for movement of sulfate and potassium through coarse-textured soils.

2.0 Methods and Materials

Four S and four K field trials were established during 2011 and 2012 on irrigated sandy soils (Tables 1 and 2). Each trial was established using a split plot within a randomized complete block design. Main plots consisted of four K or S (depending on the study) rates, referred to as at-planting (AP) treatments. Potassium rates were 0, 72, 143, and 215 kg K ha^{-1}, applied as KCl (0-0-50 NPK). Sulfur rates were applied at 0, 14, 28, and 42 kg S ha^{-1} using $(NH_4)_2SO_4$ (21-0-0-25 NPKS). Each main plot was divided into four sub-plots, referred to as in-season (IS) treatments, and identical rates of either K or S applied to each sub-plot. Each AP main plot and IS sub plot combination was replicated four times. Potassium was broadcast and incorporated prior to planting. Sulfur was applied on the soil surface within one to two days of planting. In-season sub-plots were side dressed at the V3-V5 corn growth stages by broadcasting fertilizer on the soil surface between the corn rows. The AP main plot dimension was 9.1 m wide by 21.3 m long. Plot size was increased at Sites 1 and 3 in the K study to 10.7 m wide due to the type of irrigation used at this location. Sub-plots were half the length and width of each main plot (4.55 m wide by 10.65 m long).

Pervious crops include corn or rye (*Secale cereale* L.) depending on the location (Tables 1 and 2). Other fertilizers that were not studied in these experiments were kept at non-limiting rates. Management practices such as tillage, hybrid selection, irrigation, and pest control were used as recommended for the growth in these field conditions. Total amount of irrigation water applied over the growing season varied by location. For the K study, 1156, 822, 1829, and 1644 cm^3 of water was applied at sites 1 through 4 respectively. Total amount of irrigation water applied for the S study sites is summarized in Table 16.

Eight soil cores were taken from each replication at multiple depths (0-15 cm, 15-30 cm, and 30-60 cm) for assessment soil K or S concentrations in the upper soil profile before AP fertilizer application. Composite sample consisting of twelve soil cores was taken from each sub-plot at 0-15 cm to assess variability of K or S within the study area. All samples were placed in a forced-air cabinet and dried at ambient temperature. All soil samples from the top 15 cm were analyzed for Bray-P1 P (Frank et al., 1998), soil pH [1:1 soil:water (Watson and Brown, 1998)], soil organic matter [loss on ignition (Wang and Anderson, 1998)], NH_4OAC-K extractable K (Warncke and Brown, 2011) and mono-calcium phosphate extractable SO_4^{2-}-S (Combs et al., 1998). Samples taken at the 15-30 and 30-60 cm depth were only analyzed for K or S depending on the study. Additional multi-depth samples were collected from 0-15, 15-30, 30-45, 45-60, and 60-75 cm depths at the end of the season from sub-plots where lysimeters were installed.

Prior to drying, K study soil samples collected from 0-15 cm were stored moist in sealed plastic lined bags then sieved through a 5 mm screen. Half of each sample was re-sealed in plastic lined bags and stored in coolers and the other half was dried at ambient air temperature. Samples stored in the coolers were analyzed by the ammonium acetate method on field moist samples using the direct sieving method outlined by Gelderman and Mallarino (2011). Briefly, a 2 g oven dry equivalent weight of soil was analyzed for K by the NH4OAC-K method outlined by Warncke and Brown (2011).

Cation exchange capacity was determined using ammonium saturation and displacement method on K study soil samples (Burt, 2004). Particle size analysis was determined using the pipette method at each K site (Gee and Bauder, 1986). Total S was determined using Variomax CNS combustion analyzer (Variomax CN, Elementar Americas Inc., Mt. Laurel, NJ). Total soil K was determined by inductively coupled plasma (ICP) spectroscopy using a PerkinElmer Optima 3000 (PerkinElmer Inc., Waltham, MA) following microwave digestion [EPA method No. 3051 (USEPA, 1992)].

Stand counts were taken between the V4-V6 growth stages from 12.2 m of row. Whole plant samples were taken from all sub-plots at approximately V5-V8 by cutting 8 plants at the soil surface. The leaf opposite and below the ear was sampled at R2 as a single composite samples consisting of ten leaves. Plant samples were dried at 60˚C for 7 days, weighed (V5-V8 plant samples only), and then ground to pass through a 1 mm screen. Grain sub-samples collected at harvest were dried at 100°C and ground using a flour mill. Total K in the plant tissue and grain was determined using ICP following wet digestion with nitric acid and hydrogen peroxide (Wolf et al., 2003). Total plant or grain N and S was determined using a Variomax combustion analyzer.

Normalized difference vegetation index (NDVI) readings were taken directly over the middle two rows between V5-V10 using a Greenseeker model 505 (Trimble, Sunnyvale, CA) and a Crop Circle ACS-470 (Holland Scientific Inc., Lincoln, NE). Chlorophyll readings were taken at R2 and R4 growth stages from the leaf opposite and below the ear and consisted of 30 readings per plot using a SPAD chlorophyll meter (SPAD-502, (Konica-Minolta Inc., Osaka, Japan).

Grain yield measurements were taken by hand harvesting from the two middle rows of each sub-plot. Approximately 6.1 m of row was harvested, shelled, and then weighed to determine yield. Grain harvest moisture was determined by weighing a sub-sample of grain before and after drying at 100°C. All grain yields reported were corrected to 155g kg^{-1} moisture.

A subset of four AP and IS treatments were selected for the installation of lysimeters. Plots where lysimeters were installed received either the (1) zero K or S AP and zero IS rate (zero-zero), (2) zero AP, high (42 kg S ha^{-1} or 215 kg K ha^{-1}) IS rate (zero-high), (3) high AP and zero IS rate (high-zero), and (4) high AP and high IS rates (high-high). Suction lysimeters were constructed using PVC pipes and model B02M2 (Soil Moisture Corp., Santa Barbara, CA) ceramic soil moisture suction cups. The ceramic cups were selected as they have been shown to have causes little to no adsorption of K (Vandenbruwane et al., 2008). Silica slurry was placed in the bottom of the lysimeter holes covering the ceramic suction cup in order to maintain contact between the cup and soil. Lysimeters were installed into the plots so the ceramic tips were located 60 cm deep in the soil profile. A thin layer of bentonite clay was placed on the soil surface around the lysimeter to prevent water from draining down the side of the tube. Soil water samples were collected on a weekly basis and after major rainfall events that totaled 5.0 to 7.5 cm within a daily period. Once water samples were extracted and the lysimeter was emptied, approximately 345 MPa of vacuum was applied to the lysimeters. Weekly water samples served as a way to monitor general nutrient movement through the profile over time, not for exact amounts of nutrients lost through leaching events. Potassium concentration in water was determined using ICP. Water samples from S studies were analyzed by ion chromatography using a Dionex 120 ion chromatograph (Dionex Corporation, Sunnyvale, CA) for SO_4^{2-}-S.

Statistical analysis was performed using SAS (SAS institute, 2011). All data were subjected to an analysis of variance by location using PROC GLIMMIX assuming fixed effects of fertilizer application and rate for AP or IS treatments, and random block effects. If the analysis indicated a significant interaction, least squares means were studied using the SLICE option to determine the effect of IS treatment within each AP treatment. Lysimeter and end of season multi-depth soil data was analyzed using repeated measures in PROC MIXED. Relationships between variables were examined using the PROC REG and PROC NLIN procedures. Effects were considered significant at the $P \leq 0.10$ probability level. All analyses were conducted by site.

3.0 Results and Discussion

Sulfur Study

3.1 Results

3.1.1 Soil Test Variability

Selected chemical characteristics before treatment application are given in Table 3. The pH for all sites ranged between 5.3 and 6.5 with OM contents ranging from 11 to 28 g kg^{-1}. Bray-soil test P tested in the Very High range indicating P was likely not limiting at any site (Kaiser et al, 2011). Average soil K was in the Medium range at Site 2, in the High range at Site 4, and Very High at Sites 1 and 3.

Soil samples from 0-15 cm were taken in the spring from each sub-plot to assess within site variability (Table 3). Mean soil SO_4^{2-}-S across sites ranged from 3.0 to 4.7 mg kg^{-1} in the top 15 cm. According to Rehm and Schmitt (1989) sandy soils testing in the 0-6 mg kg^{-1} range fall into the low range and are likely to respond to S fertilizer. Standard deviations ranged from 0.61 to 1.33 mg kg^{-1}, suggesting that the variability was small within each site prior to treatment application.

Multi-depth composite soil samples of each site were taken in the spring to determine total S and available SO_4^{2-}-S in the top 60 cm (Table 3). As depth increased, total S concentration varied slightly or not at all. Concentration at 0-15 cm ranged from 0.78 to 1.15 g kg^{-1}. These results indicate that SO_4^{2-}-S extracted accounts for <1% of total S in the soil at all sampling depths. The difference between the two values is likely from S contained in SOM as past research has indicated SOM is a major contributing pool to available S for the plant through the process of mineralization (O'Leary and Rehm, 1991; Kim et al., 2013).

3.1.2 Early Plant Growth, Whole Plant S Concentration, and S Uptake

Corn whole plant samples were collected near the V5-8 growth stage to assess early plant mass and nutrient uptake from applied fertilizer S. Plant mass was significantly ($P \leq 0.10$) increased by S applied AP at Sites 1 and 4 (Table 4). No significant difference in early plant mass was found at Sites 2 and 3. In-season application did not increase early plant mass for any site. Other studies have examined the impact of S on early plant mass. Rehm (1984) found no early plant mass response with increasing S fertilizer rates. Kim et al. (2013) found S increased plant mass at one of four sites but only when S was applied with P on a sandy soil. It should be noted that prior to plant sampling at the V5-8 growth stages, Site 1 presented physical evidence of smaller plants, especially in the zero-zero fertilizer rates which would indicate a potential deficiency. Differences among treatments at Site 1 and 4 may have been caused by reduced growth from S deficiency rather than growth promotion from fertilizer application. Any physical symptoms of S deficiency were not evident by the time of early plant sampling.

Whole plant S concentration was consistently and significantly affected by S fertilization. A significant interaction was found at Site 2 between AP and IS rates (Table 5). The significant interaction at Site 2 was due to linear increases in S concentration from fertilizer applied AP but only with no IS fertilizer application. A similar effect was found at Site 2 for IS fertilizer application but only when no AP fertilizer was applied.

Combinations of AP and IS fertilizer resulted in higher S concentration but were not significantly different. At each site, except Site 1, S application IS increased whole plant S concentration (Table 5). Sulfur plant concentration increased as IS fertilizer rate increased. Sites 2 and 3 also resulted in significant differences among AP fertilizer treatments. This suggests that, while different S fertilizer rates only had an effect on plant's growth at half the sites, the plants at most of the sites were able to obtain more S than needed for plant growth, luxury consumption, with increasing supplies of S from fertilizer.

Plant S uptake at the V5-V8 growth stage was significantly affected by the application of S at three sites. Sulfur applied AP significantly increased S uptake at Sites 1 and 4. At both sites, the two highest fertilizer rates were significantly greater than the lower two rates (Table 6). Sites 2 and 4 differed in S uptake for IS treatments, following a similar pattern as above. Since plant weights were significantly different at Sites 1 and 4, uptake was a direct response of greater plant mass. However, there were no differences in plant mass among treatments at Sites 2 and 3 but uptake was increased by IS rate at Site 2 and both AP and IS main effects were close to the accepted significance level at Site 3. Increase in uptake or concentration without direct increase in plant mass suggest luxury consumption of S. This agrees with other corn S fertilizer studies commonly using uptake measurements to evaluate the nutrient status of corn plants during early growth and indicate that S uptake with increased S fertilizer rates without differences in plant mass (Rehm, 1984; Rehm, 2005; and Pagani and Echerverria, 2011).

Plant NDVI measurements were assessed at the time of early plant sampling. No treatment differences were detected for V5-8 NDVI except for at Site 4 (Table 7). At Site 4, the zero AP rate was found to be significantly lower compared to other treatments. Plant NDVI readings plotted against early plant weights did not result in a strong correlation. Greenseeker NDVI is considered a useful tool for predicting plant mass. However, plants may have already been too large to see differences between treatments. If NDVI readings had been taken earlier in the growing season while there were physical evidence of different plant mass, a better relationship between NDVI and plant mass may have been found. This data would suggest using NDVI readings at an earlier growth stage are not useful for detecting S availability.

3.1.3 Mid-Season S Availability

Ear leaf samples collected at the R2 growth stage were analyzed for S concentration. In-season application of S significantly increased ($P \leq 0.10$) ear leaf S concentration at three of four sites. Sulfur concentration for the 42 kg S ha^{-1} IS rate produced the greatest concentration among treatments (Table 8). Sulfur concentration among AP rates significantly differed at two sites. Within these sites, 42 kg S ha^{-1} produced the greatest ear leaf S concentration. Unexpectedly, the 14 kg S ha^{-1} AP rate produced the lowest concentration but was not significantly different from the 0 or 28 kg S ha^{-1} rate. These data suggest an increasing relationship in ear leaf S concentration from increasing rates of fertilizer applied AP. There was greater variability among the data for AP fertilizer rate treatments versus IS application.

Sites where there were significant differences in V5-8 whole plant S concentration (Table 5) corresponded with sites ear leaf S concentration differed. This suggests the uptake of S later in the growing season follows a similar pattern as early season uptake. All ear leaf S concentration were considered sufficient (<2.0 g S kg^{-1}), thus the corn plants acquired sufficient amounts of S needed for growth (Kaiser et al., 2013). Ear leaf S concentration was plotted against grain yield over all sites. No significant correlation was found between ear leaf S concentration and grain yield, contrary to the results of O'Leary and Rehm (1990).

For a plant to properly produce proteins and regulate its metabolism, it requires certain quantities of both N and S. Plant tissue N and S concentration ratios are often used to determine if a plant has a sufficient amount of both to properly grow. Various studies have indicated that when a N:S ratio is greater than 15:1 the plant is considered to have insufficient amounts of these nutrients to properly synthesis proteins and maintain metabolism (Stewart and Porter, 1969; Cassel et al., 1996). Ear leaf samples taken at R2 growth stage were used to compare N and S concentration ratios. No combination of AP or IS treatments yielded ratios that were considered to be insufficient (Table 9). All plants in this study had sufficient amounts of N and S to maintain metabolism and to properly produce proteins, even zero rate treatments. No significant differences in N:S ratios were found at the Sites 1 or 3, but there were significant different for IS treatments at Sites 2 and 4. Nitrogen to S ratios decreased with increasing fertilizer rates, as would be expected from ear leaf S concentration results. Site 4 also had significant differences among AP fertilizer treatments but not there was no general correlation between the N:S ratio and fertilizer rates. While not measured in this study, earlier plant N:S ratios could prove to indicate insufficiencies if taken at an early growth stage where physical deficiencies are seen.

Leaf greenness of ear leaves was assessed at the R2 and R4 growth stages with SPAD chlorophyll meters. Only IS fertilizer application had a significant impact on leaf greenness at the R2 growth stage at Site 4 (Table 10). Greenness increased with increasing IS fertilizer rate. These assessments are often associated with N status of plants (Blackmer and Schepers, 1995; Bullock and Anderson, 1998; Costa et al., 2001). However, there was no evidence that N concentration differed among treatments (data not shown) nor could any differences be associated with ear leaf S concentration or N:S ratio. Further SPAD measurements were taken at R4, and similar results were found (Table 11). Chlorophyll measurements at R2 and R4 were also used to see if leaf greenness due to crop S status could be a potential predictor of grain yield as suggested by Pangani and Echeverria (2011) but no correlation was found (data not shown).

3.1.4 Corn Yield and Harvest Variables

Grain yield, grain S concentration, grain S removal, and grain moisture did not significantly ($P \leq 0.10$) differ among fertilizer rates at any site even though there was evidence of luxury consumption earlier in the study (Tables 12 through 15). This suggests that any S fertilizer additions to these sites were not beneficial for increasing grain yields. Split-applications were not beneficial to grain yield either.

Lack of response in corn grain yield was surprising despite soil tests values which suggest a greater probability of crop response. A potential reason for lack of response could include adequate supply of SO_4^{2-}-S from SOM, having ample time to mineralize during the growing season (O'Leary and Rehm, 1991). Other research has suggested that variations in SOM can make a bigger difference in crop grain yield than S fertilizer applied (Kim et al., 2013). Other potential S inputs could result from irrigator water with a high enough S concentration from the surround well waters. Well water samples were taken at the end of the growing season and found SO_4^{2-}-S concentrations ranging from 9 to 21 mg S kg^{-1} (Table 16). Taking into account the amount of irrigation water supplied, the rates of SO_4^{2-}-S applied by irrigation roughly works out to have applications of 8 to 17 kg S ha^{-1}, which correspond to current fertilizer application guidelines (Kaiser et al., 2011). It is very likely that ample S was applied from irrigation water alone over the growing season to meet the crop's needs and limited the potential crop response from S fertilizer.

3.1.5 SO_4^{2-}-S Concentration in Soil Pore Water and Fall Soil Samples

Daily precipitation data were considered for potential leaching due to heavy rainfall events. The highest daily totals, 19.8 mm and 88.3 mm, were observed at Site 1 in 2011 and at Site 3 in 2012, respectively. Precipitation was totaled for each month and compared to the 30 year normal for each site (Table 17). At Site 1, precipitation was below normal for all months except in June. Rainfall in April, May, and July was near normal at Site 2 but was greater than normal in June. In the months of August and September Sites 1 and 2 were at least 20 mm less than normal. Site 3 had above normal rainfall in April through June. June was over 100 mm above normal. July through August at Site 3 was below normal rainfall. Site 4 had relatively normal rainfall in April and July, but was 58 mm above normal in May. The rest of the months were considered below normal. The later months of the growing season were drier than normal, a large area of Minnesota being in a drought in 2012.

Weekly water samples were taken to examine the pore water SO_4^{2-}-S concentration throughout the growing season. Site 1 had fairly small SO_4^{2-}-S concentration through the first few weeks and saw a substantial concentration increase after the IS fertilizer application followed by a sharp decrease (Figure 1). Water SO_4^{2-}-S concentration significantly ($P \leq 0.10$) differed among treatments at sampling dates 175 to 206 and at day 270. The high AP treatment had significantly greater SO_4^{2-}-S concentration over the zero AP treatments. Since both high-zero and high-high treatments saw a concentration spike after IS application, nutrient movement during this time most likely is attributed to intense rainfall rather than the IS fertilizer application. Sulfate-S concentration at Site 1 remained constant until the last two weeks where there was a general increase at end of the growing season until harvest. At day 270 SO_4^{2-}-S concentrations for high-high and zero-high treatments were significantly greater than the zero-zero and high-zero treatments. This indicated that IS applications were beginning to increase SO_4^{2-}-S concentrations at the 60 cm soil depth at the end of the growing season. This implies that any S fertilizer applied AP had already moved below 60 cm.

Site 2 exhibited no signs of a large increase in SO_4^{2-}-S concentration after the IS fertilizer application (Figure 2). Sulfate-S concentration for all treatments remained constant until calendar day 190 where the high-high fertilizer treatment concentration started to dramatically increase compared to the other three treatments which did not differ. The high-zero and zero-high treatments at calendar day 230 were significantly greater than the zero-zero but were generally less than the high-high treatment. This indicates there was some movement when 42 kg S ha^{-1} was applied either AP or IS, but the potential for movement was greater when fertilizer was applied at both AP and IS application times.

Site 3 did not show a clear trend except for the zero-zero treatment which remained fairly constant throughout the growing season (Figure 3). All other treatments that received fertilizer were generally greater than the zero-zero rate and while variable, all treatments tended to increase towards the latter half of the growing season. There was no evidence of a large movement of SO_4^{2-}-S after IS fertilizer application. The only date that had significantly different SO_4^{2-}-S concentrations was day 217 where the high AP treatments concentrations were significantly greater than the zero AP rate treatments.

There were no differences among treatment for most of the growing season at Site 4 (Figure 4) except towards the end of the sampling where all treatments were found to have greater pore water S concentration than the control (zero-zero).The concentrations at Site 4 followed a similar pattern as Site 2 where high-high treatment produced the greatest SO_4^{2-}-S concentration near the end of the season. The next largest concentration was produced by the high-zero treatment which indicated that the AP fertilizer application provided the greatest movement of SO_4^{2-}-S in the top 60 cm. There was no difference between the zero-zero and the zero-high treatments SO_4^{2-}-S concentration at the end of the growing season. This would indicate that the IS fertilizer application alone did not result in the movement of SO_4^{2-}-S to 60 cm.

Sulfate concentration did tend to increase towards the end of the growing season. However, the high-high fertilizer treatment was often much greater in soil water SO_4^{2-}-S concentration versus the other treatments. Large or multiday rain events did not seem to affect the movement of SO_4^{2-}-S in the soil profile with the exception of at Site 1. The majority of soil water SO_4^{2-}-S concentration seemed to range between 0 to 40 mg S kg^{-1} except near the end of the growing season before harvest when SO_4^{2-}-S concentration increased towards 60 mg S kg^{-1}. Increases at the end of the growing season may have resulted from low lysimeter water volumes which resulted in greater concentration. No concentration spikes were seen early in the growing season, with the exception of Site 1. This data suggests that split application of fertilizer are not necessary unless heavy rainfall occurs early in the growing season.

Fall multi-depth soil samples showed similar SO_4^{2-}-S concentration with depth among treatments (Table 18). The main of effect of AP fertilizer rate was significant at three sites, IS was significant at two, and the interaction between AP and IS was significant at one. The significant interaction occurred at Site 4 where the 42 kg S ha^{-1}applied AP and IS had the greatest average SO_4^{2-}-S concentration. The concentration was smallest when no S fertilizer was applied, and there was no difference when 42 kg S ha^{-1} was applied either AP or IS. Main effect differences at Site 1 and 2 indicate greater SO_4^{2-}-S concentration when 42 kg S ha^{-1} was applied at either AP or IS.

The main interest was to study treatment interactions with soil depth. Average SO_4^{2-}-S concentration varied by depth at two sites as expected. However, there was little interaction between treatments and sampling depth. Closest values to the accepted significance level occurred at Sites 1 and 3 where depth interacted with either AP or IS treatments at P=0.30. At Site 1 the increase in SO_4^{2-}-S due to 42 kg S ha^{-1} AP trended higher at the 30-45 cm depth. Similar effects occurred at Site 2 but occurred at the 15-30 and 30-45 cm depths. Overall, the lack of significance resulted in difficulties interpreting the effects on soil versus pore water SO_4^{2-}-S concentrations. Soil pore water SO_4^{2-}-S concentration was probably a better indicator of SO_4^{2-}-S loss compared to soil SO_4^{2-}-S concentration.

Potassium Study

3.2 Results

3.2.1 Soil Test Variability

Selected chemical characteristics of soils before treatment application are given in Table 2. The pH for all sites ranged between 5.4 and 6.9 with OM contents ranging from 11 to 39 g kg^{-1}. Bray-P1 average soil tests for sites 2, 3, and 4 were Very High and site 1 tested in the Medium range (Kaiser et al, 2011). Average soil test K (NH_4OAC-K) ranged in the Low and High ranges in the top 15cm, and decreased with depth.

Multi-depth soil samples taken in the spring were used to determine CEC and particle size in 15 cm depth increments (Table 19). Soil CEC ranged from 4.5 to 14.3 $cmol_c$ kg^{-1} in the top 15 cm at all sites. These sites are typical for CEC in sandy loams or loamy sands (Jones Jr., 2011). As soil depth increased, CEC decreased and sand content increased. There was indication for greater CEC in the 15-30 cm depths, but the value was relatively consistent at each site. Sites 2 and 4 had the greatest CEC ranges which can be explained by greater concentration of clay in surface soils (0-15 cm) at those sites. Total K decreased with depth (Table 18). Decreasing total K deeper in the soil profile follows decreases in CEC. Lower CEC values indicate that less K that can be held. Site 2 had greater total K amounts even though the available soil K test tested in the Medium range (Kaiser et al., 2011). Site 4 had the second greatest total K levels and corresponded with the greatest available K all the sites.

Soil samples in the top 15 cm were taken from all sub-plots prior to fertilization to assess the variability of soil test K across the study areas (Table 20). Sites 1 and 3 tested low in K (Kaiser et al., 2012) averaging 42 and 60 mg Kg^{-1}, respectively. Site 2 tested medium (90 mg K Kg^{-1}) and Site 4 tested High averaging 157 mg K kg^{-1} in the top 15 cm. Within plot variation (indicated by standard deviation) increased as soil test K increased. Sites with high standard deviation resulted in a greater range of potential response to K fertilizer. Site 4 had the highest standard deviation, 34.4, in soil test K in the top 6 inches. Site 4, which tested High to Very High in soil K test, would have had a very low probability of a yield response occurring compared to Sites 1 and 3 where the probability of a grain yield increase from fertilizer K would have been greater. Site 1 had the smallest standard deviation, 8.7 mg K kg^{-1}, and the smallest soil test K thus should have a better chance of a significant yield response.

The ammonium acetate K (NH_4OAC-K) test was utilized to compare two analysis methods, testing on field moist and air dry soils. Air drying of soil samples is currently the accepted method for labs to use when analyzing soil test K. Research in Iowa has found improvement in the assessment of K availability to crops when testing soil samples on a field moist basis for some soils (Mallarino, 2012; Mallarino, 2012b). Most of this research was conducted on medium to fine textured soils thus the effect of coarse textured soils is unknown. There was a strong linear correlation ($R^2 = 0.91$) between the two tests and no evidence that the linear coefficient differed from 1(Figure 5). These results suggest that there is no difference in dry versus moist soil test methods for these coarse textured soils.

3.2.2 Early Plant Growth, Whole Plant K Concentration, and K Uptake

Early corn plant samples were taken to assess the early plant mass differences and the nutrient uptake of K from single and split applications. There was no significant ($P \leq 0.10$) increase in plant mass early in the season from AP or IS fertilizer application at any site (Table 21). However, significant differences in early plant K concentration among IS treatments occurred at three of four sites. Of the three sites, the 215 kg K ha^{-1} IS treatments increased tissue K concentration more than any other treatment. Samples were collected at an early growth stage at Site 1 close to the time of the IS application thus it is unlikely that any increase would be possible by the time samples were collected. As IS treatment rates increased so did plant sample K concentration. Significant differences occurred between AP K treatments at three of four sites. As seen with IS treatments, as AP fertilizer rate increased so did early plant K concentration. Significant interactions occurred among AP and IS rates in Sites 3 and 4 (Table 22). All combinations, except the zero-zero rate, followed a similar pattern in which K concentration increased with increasing AP and IS rate. Zero AP concentration followed a similar relationship except for the zero-zero rate combination which had a much smaller concentration. Site 4 suggested that while there was an interaction between AP and IS rates, IS rates being the main effect of K concentration.

Early plant K concentration was plotted against grain yield to look for a correlation or a critical concentration as found by Clover and Mallarino (2013), but no relationship was found (data not shown). It should be noted that all early plant K concentration were above the critical level found by Clover and Mallarino (2013) which may explain why no relationship was found between grain yield and early plant K concentration. Early plant K concentration was not found to be able to predict yield.

Early plant K uptake was calculated from plant mass and K concentration to determine potential luxury uptake of K. Significant differences occurred among AP treatments at Sites 1, 2, and 3. Early uptake of K increased as fertilizer K rates increased (Table 23). Significant differences were found among IS treatments at Site 3 but there was no relationship between increasing AP or IS rate and increasing uptake of K. Considering that plant weights for all treatments were not significantly different but plant K concentration was, there is evidence that luxury consumption was occurring. This suggests that any added K fertilizer at the V5-8 growth stages only resulted in luxury consumption and was not beneficial to plant biomass production. This data agrees with the findings of Clover and Mallarino (2013). They reported no differences in early plant weights but found significantly different K uptake at a majority of locations studied. Lower K uptake response for the high fertilizer rates at Site 2 may be because of a medium K soil test at the start of the study. Uptake did not differ for any treatment at Site 4 which tested in the high range for available soil K at the start of the study.

Plant NDVI readings were taken at the V5-V8 growth stages. Treatments affected NDVI only at Site 2 (Table 24). At Site 2 AP treatments were significantly different but higher fertilizer rates did not translate to larger NDVI values. NDVI plotted against early plant weights indicated a strong exponential relationship ($R^2 = 0.81$, $P < 0.0001$), but was dependent on site (Figure 6). As NDVI readings increased, plant weights increased exponentially, suggesting that NDVI readings for K studies can help predict plant biomass production. It should be noted that this relationship is highly dependent on the collection of plants sampled at different growth stages between V5 and V8. Plant weight NDVI correlation at Site 1 alone had a linear relationship ($R^2 = 0.62$, $P<0.0001$).

3.2.3 Mid-Season K Availability

Ear leaf samples collected at the R2 growth stage were analyzed for K concentration. Tissue K concentration significantly ($P \leq 0.10$) differed among AP fertilizer treatments at all four sites (Table 25). The zero AP fertilizer rate had significantly lower K concentration at all sites. As AP fertilizer rates increased so did plant K concentration. Similar relationships occurred in three of four sites for IS treatments, again with zero rate treatments exhibiting significantly lower K concentration. Significant interactions between AP and IS were found in three of four sites. Significant interactions were due to greater effect of IS treatments for the two lowest AP rates. The greatest increase in ear leaf K concentration occurred when IS fertilizer was applied with no AP fertilizer. There was less K concentration response when fertilizer was applied IS on plots with AP fertilizer treatments (excluding the zero AP treatment). When comparing ear leaf K concentration from similar fertilizer rates applied AP or IS, there was no evidence of a difference among application timings. This indicates that the relative efficiency of the two timings were relatively similar.

Ear leaf concentration was studied to determine if it related to grain yield over all sites to determine if ear leaf samples could be used as a predictive tool for grain yield as has been previously noted (Clover and Mallarino, 2013). No significant correlation was found for ear leaf K concentration and grain yield (data not shown). As with early plant K concentration, ear leaf K concentrations were all well above the critical level, 11.0 g K kg^{-1}, found by Clover and Mallarino (2013) which may help explain why no relationship was found.

It has been found that the amount of N taken up by a corn plants can have an effect on the uptake of K, and vice-versa (Jones et al., 1991). Corn response to N or K can depend on whether the other is present in sufficient levels, and excessive K has been known to cause

N deficiencies (Bromley, 2013). Guidelines given for N:K ratios in plant tissue range from 0.8 to1.6. (Espinoza and Ross, 2010) or 1.2 to 2.2 (McGinnis and Stokes, 2012). Nitrogen:K ratios were compared for ear leaf samples around the R2 growth stage. Since no differences were seen in leaf N concentration, the sites that had significantly different K concentration for AP and IS treatments had significantly different ratios between N and K (Table 26). Differences in N:K ratios were dependent on leaf K concentration. Nitrogen:K ratios decreased as fertilizer treatments increased for AP and IS treatments, as expected. Zero AP and IS rate N:K ratios were significantly larger than higher fertilizer treatments at all sites. Almost all N:K ratios fell between the guideline range given by Espinoza and Ross (2010) and McGinnis and Stokes (2012). Nitrogen:K ratios were also compared to grain yield to see if there was correlation between the two as found by Dibb and Welch (1975) where yield decreased with increasing N:K ratio. No relationship was found between N:K ratios and grain yield.

Ear leaf SPAD chlorophyll meter readings were taken at R2 and R4 growth stages to assess leaf greenness and potential differences due to low K availability. There were no significant differences in ear leaf greenness at R2 except at Site 4. The at-planting treatment had a significant effect on ear leaf greenness at Site 4 (Table 27). Opposite to what was expected, as AP fertilizer rate increased, leaf greenness decreased. Readings at R4 produced similar results with only AP treatments being significantly different at Site 4 (Table 28). SPAD readings were plotted against ear leaf N:K rations but no relationship was found (data not shown).

3.2.4 Corn Yield and Harvest Variables

Main treatment effects on corn grain yield, grain moisture, and grain K removal were not significantly (*P*≤0.10) different at any site (Tables 29 to 32). No significant differences were found in grain K concentration for any site except for Site 2 (Table 30) where there were differences only among the AP treatments. Soils testing in the Medium and High class soil K would present a less likelihood for a grain yield response to K. However, two sites tested Low or Very Low in soil K. Even though split applications of K fertilizer are not recommended for these soils, a grain yield response should have been likely when soil test K was low. Why no yield response occurred at the other two sites is unknown. Irrigation water may have provided some small K inputs, but well water samples indicated that K concentration in irrigation water were lower than the detection limit of the ICP (<0.30 mg K kg^{-1}). Considering the detected limit level of K and the amount of irrigation water applied, application would have totaled less than 1 kg K ha^{-1} which would not supply enough K to the crop to make an impact on grain yield.

3.2.5 Concentration of K in Soil Pore Water and Fall Soil Samples

Daily precipitation data was considered for the potential for leaching due to heavy rainfall events. The highest daily total, 22.6 mm and 15.6 mm, was observed at Site 1 in 2011 and at Site 3 in 2012, respectively. Totaled monthly rainfall data were collected at each site and were compared to the 30 year monthly normal (Table 33). At Site 1, rainfall in April, May and July was above the 30 year normal, while the other remaining months were below normal. The precipitation at Site 2 was relatively close to the normal in the months of April, May, and July and slightly greater in June. Rainfall in August and

September was below the normal by about 20 mm. Site 3 had under normal rainfall through the growing season except in May, where the monthly total was 78 mm above the 30 year average. Site 4 also saw a higher than normal rainfall total in May. About normal rainfall was seen in April and July, and was under normal in the remaining months.

Soil pore water K concentration was monitored weekly from select treatments to assess the potential for K movement. Soil pore water K concentration at Site 1 was relatively consistent throughout the growing season. Around day 180, a large peak in K concentration was found among all treatments (Figure 7). This peak occurred shortly after the IS fertilizer application and effected all four treatments, suggesting that the IS fertilizer application may have been the cause for this spike. While there was a multi-day rainfall event leading up to this spike in concentration, rainfall was relatively small and most likely was not a major contributor. Potassium concentration significantly ($P \leq 0.10$) differed among treatments on calendar days 143, 187, and 192. The high IS application rate was significantly greater than the zero IS rate on days 187 and 192. At the day 143 the high AP rate concentration was significantly greater over the zero rate concentration.

At Site 2 all treatments decreased in K concentration from the beginning of the growing season to the end where it stabilized at day 200 (Figure 8). The high-high fertilizer treatment was significantly greater than the other three treatments but could have been potentially caused by soil contamination from the upper soil surface during lysimeter instillation. This especially large concentration is puzzling as the high-zero concentration was much less suggesting soil contamination was possible in the high-high plots. Potassium concentration at sampling days 143 to 169 was significantly different between treatments where the high-high rate was significantly greater than all other treatments. Only the high-high rate treatment made any real difference in nutrient movement at this location.

Site 3 was similar to Site 2 where K concentration started large among all treatments, even the zero-zero rate, and then decreased through the growing season (Figure 9). Potassium concentration became steady around day 180 for all treatments and then increased at the end of the sampling. At the beginning of the study K concentration in the high AP treatments seemed to be much greater than the zero AP concentration. Conversely, at the end of the growing season the high IS treatments had much greater K concentration than the zero IS rates. This suggests that IS applications had a role in K movement during the growing season. Only sample days 149 and 155 were found to be significantly different at this location. This site indicates that the high AP treatments had significantly greater K concentration over the zero AP rates.

Site 4 K concentration decreased from the start of the growing season and stabilized until day 220. At that time the K concentrations for the two high IS treatments increased dramatically in the final weeks (Figure 10). The zero-zero rate and the high-zero rate treatment concentration remained consistent through the end of the growing season. The zero-high treatment seemed to have dramatically increased in the last two weeks of sampling, but may be because of empty lysimeters late in the season. Pore water K concentration significantly different among all treatments from day 217 to 232. At these sampling dates the high-high treatment K concentration was significantly greater than all other treatments except on the last sample date. On the last sampling date the concentration increased for the zero-high treatment. This may be caused by a lack of water samples at the end of the growing season as rain decreased.

Soil pore water data from all sites showed a spike in K concentration at the beginning of water sampling. It is possible that this spike could have resulted from contamination from lysimeter installation. This was seen at all locations and zero-zero rates also saw decreases in K concentration. There may be K movement early in the growing season as a result of high rainfall events prior to sampling and the potential that K did not have enough time to interact with the CEC in the soils or be taken up by plants at this time. If this is true, split applications may help farmers maintain greater K availability and lose less fertilizer due to leaching. Installing lysimeters weeks before fertilizer is applied to fields may help give a better picture of what is happening with K in the soils earlier on and whether these concentration spikes are a result of contamination or actual K movement. Pore water K concentration at the beginning of the studies often was often at greatest at the high AP rates. At the end of the growing year, often the high IS treatments had the greatest concentration. This suggests that IS fertilizer application has an effect on K concentration.

Multi-depth soil samples were taken at the end of the growing season to assess the final concentration of K in the soil profile (Table 34). Main effects of AP fertilizer treatments were significant at two sites and the IS main effect was significant at three sites. There was a significant interaction of AP and IS treatments with depth at Site 1, 3, and 4. This indicates that main effects occurred only at certain depths in the soil profile. In all cases, all significant differences occurred at the 0-15 cm depth. At two locations, Site 3 and 4, the increase in soil test K was greatest from IS fertilizer treatments. At these sites 215 kg K ha^{-1} applied AP resulted in greater soil test values than the control, but were still less than the 215 kg K ha^{-1} applied IS. At Site 1, the soil test increase was similar for 215 kg K ha^{-1} applied IS or AP, and the greatest increase occurred when fertilizer was applied at both timings.

Soil test results from 0-15 cm for Sites 2 and 3 indicate some potential movement from the applied AP fertilizer treatments. The split application seems to retain more available K in the top 15 cm of the soil profile. However, below 15 cm there is no evidence of K movement for any fertilizer treatment. This may provide additional evidence to the initial spike in soil pore water K concentrations seen at most sites was a result of rapid leaching of K. A small increase would be expected at deeper depths but may not be able to be detected at the given probability level. However, given the low CEC of these soils, it is possible that K would be poorly retained given a large enough rainfall events to move K rapidly through the profile specifically through macropore flow which agree with findings by Alfaro et al. (2004). This indicates that there is a great potential leaching loss of K, however plant data suggests that there was enough K available to the crop.

4.0 Conclusion

Evaluations of K^+ and SO_4^{2-} availability over the growing season indicated that corn plants were able to take up adequate amounts of these nutrients. While early plant mass did not significantly differ between treatments in either S or K studies, plant S or K concentration and uptake were significantly affected by treatments. Both AP and IS fertilizer applications increased concentration and uptake of K and S. Increased uptake and tissue K or S concentration without a resulting increase in plant mass suggested luxury consumption of both S and K early in the growing season.

Mid-season ear leaf concentrations were sufficient for both S and K. Ear leaf concentration differed among AP and IS treatments at the same locations where early plant concentrations were significantly different. Three of four K sites had significant interactions between AP and IS applications and their effect on ear leaf concentrations. The greatest ear leaf K concentration response occurred when IS fertilizer was applied with no AP fertilizer. Data also suggested that the relative efficiency of the two fertilizer timings were similar. Ear leaf N:S and N:K ratios were sufficient for proper plant growth and nutrient uptake. Sulfur and K ear leaf concentration was not a predictor for grain yield.

No combination of fertilizer applications had any significant difference between grain yield, S or K removal in grain, or grain moisture in both studies. Grain S and K concentrations were not significantly different between treatments except at Site 2 in the K study. This site only indicated significant differences in the AP treatments but had no clear relationship. Split application did not indicate any benefit to grain yield, and no fertilizer rates provided a response in yield.

Various remote sensing tools were used throughout the growing season to predict plant biomass, predict grain yield, and to assess for plant S and K deficiencies. Plant NDVI readings taken by Greenseeker in both studies were found to be a good predictor of plant mass in the K studies. For both S and K studies, NDVI readings did not indicate any significant differences of plant mass among any combination of AP and IS rates. Taking earlier NDVI readings may prove to be more useful for differences or deficiencies between treatments. SPAD chlorophyll meters used to assess leaf greenness at R2 and R4 growth stages found only significant differences at one site in each S and K studies. SPAD readings were also used to try to predict grain yield but did not indicate any relationship between the two in either study.

Soil pore water concentrations and multi-depth soil samples were used to determine the potential for movement of S or K through the soil profile during the growing season. Sulfate-S water concentrations did not provide a clear pattern throughout the growing season except for a general increase in concentration towards the end of the growing season. However, Site 1 had a large concentration spike potentially as a result of heavy rainfall events. Sulfur pore water data did not suggest the need for split application of fertilizer except for when there are heavy or excessive rain events early in the growing season. Multi-depth soil samples did not have any large variation in soil concentration with depth or among treatments. The lack of significance in soil data suggests that lysimeter water data was a better indicator of S losses than soil samples.

Potassium pore water concentration data at all sites, showed an initial spike in K soil pore water concentration then a decrease into a relatively constant level. With the exception of Site 1, no large concentration spikes were seen to suggest a large leaching event. Concentration spikes at the beginning of the growing season may have resulted from lysimeter installation contamination, but also may have occurred from early season K movement potentially due to the K not having enough time to interact with the low CEC of the soil. Installing lysimeters much earlier in the fields before initial fertilizer applications may be able to provide a much better picture of how K is moving through the soil profile prior to crop planting. Multi-depth soil samples indicated little K movement past the top 15 cm, but were able to provide effects of AP and IS fertilizer treatments at multiple sites. Two sites had greater soil test values from the IS fertilizer treatments. Site 1 indicated that the 215 kg K ha^{-1} rate applied at IS or AP increased soil test values the most. Follow-up research is suggested to determine if early-season concentration differences are a result of significant leaching of K.

Table 1. Site locations (nearest city in Minnesota), soil series information, cultural practices, and in-season (IS) fertilizer application timing at four sulfur research locations.

			Soil						Date of	
Site	Year	Location	Series	Class ‖	Texture‡	Previous Crop	Hybrid	Tillage†	Planting	IS Fert.§
1	2011	Hastings	Sparta	E. Hapludoll	LFS	Soybean	DKC48-12	CPF, SFC	6 May	13 Jun.
2		Randolph	Estherville	T. Hapludoll	SL	Corn	DKC52-59	CPF, SFC	6 May	16 Jun.
3	2012	Hastings	Sparta	E. Hapludoll	LFS	Corn	DKC48-12	CPF, SFC	4 May	30 May
4		Palmer	Hubbard	E. Hapludoll	LS	Rye	G88F73GT	CPS, SFC	24 Apr.	30 May

†(CPF) chisel plowed in fall, (CPS) chisel plowed in spring, and (SFC) spring field cultivated.

‡(LS) loamy sand, (SL) sandy loam, and (LFS) loamy fine sand.

§IS Fert., in-season fertilizer application.

‖ (E.) Entic and (T.) Typic

Table 2. Site locations (nearest city in Minnesota), soil series information, cultural practices, and in-season (IS) fertilizer application timing at four potassium research locations.

			Soil						Date of	
Site	Year	Location	Series	Class ‖	Texture‡	Previous Crop	Hybrid	Tillage†	Planting	IS Fert. §
1	2011	Becker	Hubbard	E. Hapludoll	LS	Rye	DKC48-12	CPF, SFC	30 April	13 June
2		Randolph	Estherville	T. Hapludoll	SL	Corn	DKC52-59	CPF, SFC	6 May	16 June
3	2012	Becker	Hubbard	E. Hapludoll	LS	Rye	DKC48-12	CPF, SFC	20 April	May 30
4		Palmer	Hubbard	E. Hapludoll	LS	Rye	G88F73GT	CPS, SFC	24 April	May 30

†(CPF) chisel plowed in fall, (CPS) chisel plowed in spring, and (SFC) spring field cultivated.

‡(LS) loamy sand and (SL) sandy loam.

§IS Fert., in-season fertilizer application.

‖ (E.) Entic and (T.) Typic

Table 3: Selected chemical characteristics for four sites summarized from soil samples collected at 0-15, 15-30, and 30-60 cm depths.

		Soil Test 0-15 cm†				SO_4^{2-}-S‡		
Site	Depth	pH	OM	P	K	mean	st dev	Total S
	cm		g kg^{-1}	-------------mg kg^{-1}-------------				g kg^{-1}
1	0-15	6.5	13	44	172	3.0	1.33	0.84
	15-30	---	---	---	---	5.5	---	0.78
	30-60	---	---	---	---	4.8	---	0.87
2	0-15	5.3	28	31	83	3.2	0.61	1.15
	15-30	---	---	---	---	3.5	---	1.09
	30-60	---	---	---	---	2.5	---	0.99
3	0-15	6.5	18	28	186	4.7	0.84	1.08
	15-30	---	---	---	---	2.3	---	1.08
	30-60	---	---	---	---	3.0	---	0.99
4	0-15	6.2	11	93	127	3.1	1.18	0.78
	15-30	---	---	---	---	1.9	---	0.81
	30-60	---	---	---	---	1.8	---	0.80

† P, Bray-P1 phosphorus; pH, soil pH 1:1 soil:water; OM, LOI organic matter.
‡ SO_4^{2-}-S, mean and standard deviation of the mono-calcium phosphate S extraction.

Table 4. Summary of corn early plant (V5-V8) plant mass for combinations of at planting (AP) and in-season (IS) S rates at four locations in Minnesota and main treatment effect means.

Site	AP Rate	IS S Rate (kg S ha^{-1})					Statistics†		
		0	14	28	42	Mean‡	AP	IS	AP x IS
	kg ha^{-1}	--------------mg S plant^{-1}---------------					----------*P*>F----------		
1	0	3.0	3.1	2.9	3.3	**3.1b**	**	0.33	0.98
	14	3.4	3.6	3.3	3.5	**3.5ab**			
	28	3.5	3.8	3.5	3.7	**3.6a**			
	42	3.7	3.8	3.4	3.4	**3.6a**			
	Mean‡	3.4	3.6	3.3	3.5				
2	0	11.8	11.1	10.6	11.2	11.2	0.94	0.77	0.94
	14	11.7	11.2	10.9	11.4	11.3			
	28	11.0	12.3	11.2	11.0	11.4			
	42	11.5	11.3	11.4	12.0	11.5			
	Mean‡	11.5	11.5	11.0	11.4				
3	0	16.8	17.0	16.3	18.1	17.0	0.19	0.93	0.89
	14	17.1	17.7	16.4	16.4	16.9			
	28	13.7	15.6	16.6	14.7	15.2			
	42	16.8	16.6	15.8	16.1	16.4			
	Mean‡	16.1	16.8	16.3	16.4				
4	0	13.3	13.9	15.9	12.7	**14.0b**	0.08	0.54	0.80
	14	17.0	15.8	14.6	16.1	**15.9ab**			
	28	16.8	16.6	15.4	15.7	**16.1ab**			
	42	18.8	16.2	15.9	15.3	**16.6a**			
	Mean‡	16.5	15.7	15.5	15.0				

† Denotes significance at the 0.05 (*), 0.01 (**), 0.001 (***) probability level. Effects are considered significant at $P \leq 0.10$.
‡ Numbers within same row or column followed by same letter are not significant at $P \leq 0.10$.

Table 5. Summary of average V5-8 plant S concentrations for combinations of at planting (AP) and in-season (IS) S rates at four locations in Minnesota. Treatment mean values are summarized for the AP and IS treatments.

Site	AP rate	IS S Rate (kg S ha^{-1}) 0	14	28	42	Mean‡	Statistics† AP	IS	AP x IS
	kg ha^{-1}	-----------g kg^{-1}---------------					----------*P*>F---------		
1	0	2.91	2.80	2.92	2.78	2.58	0.13	0.79	1.00
	14	3.05	3.00	2.98	3.13	3.04			
	28	3.21	3.10	3.34	3.32	3.23			
	42	3.10	3.08	3.38	3.21	3.19			
	Mean‡	3.07	3.00	3.15	3.11				
2	0	2.71	2.86	3.08	3.39	**3.01c**	***	***	*
	14	2.77	3.15	3.12	3.21	**3.06bc**			
	28	2.99	3.21	3.14	3.21	**3.14ab**			
	42	3.12	3.12	3.20	3.49	**3.22a**			
	Mean‡	**2.87c**	**3.09b**	**3.14b**	**3.36a**				
3	0	2.74	2.90	3.13	3.31	**3.01ab**	**	**	0.50
	14	2.50	3.01	2.74	3.03	**2.82b**			
	28	2.87	3.15	3.03	3.12	**3.04ab**			
	42	3.10	2.97	3.49	3.53	**3.27a**			
	Mean‡	**2.80b**	**3.00ab**	**3.09ab**	**3.24a**				
4	0	1.73	2.17	2.73	2.85	2.37	0.33	***	0.88
	14	1.71	2.27	2.58	2.69	2.31			
	28	1.71	2.29	2.44	2.38	2.20			
	42	1.99	2.25	2.62	2.95	2.45			
	Mean‡	**1.79c**	**2.25b**	**2.59a**	**2.72a**				

† Denotes significance at the 0.05 (*), 0.01 (**), 0.001 (***) probability level. Effects are considered significant at $P \leq 0.10$.

‡ Numbers within same row or column followed by same letter are not significant at $P \leq 0.10$.

Table 6. Summary of average V5-8 plant S uptake for combinations of at planting (AP) and in-season (IS) S rates at four locations in Minnesota. Treatment mean values are summarized for the AP and IS treatments.

Site	AP rate	IS S Rate (kg S ha^{-1})					Statistics†		
		0	14	28	42	Mean‡	AP	IS	AP x IS
	kg ha^{-1}	--------------mg S plant^{-1}---------------					---------*P*>F----------		
1	0	8.7	8.7	8.9	10.0	**9.0b**	**	0.87	0.99
	14	10.5	11.0	9.7	11.0	**10.5ab**			
	28	11.2	11.6	11.8	12.3	**11.7a**			
	42	11.4	11.5	11.3	10.9	**11.3a**			
	Mean‡	10.4	10.7	10.1	10.6				
2	0	31.6	31.7	32.7	39.1	33.8	0.25	*	0.57
	14	32.1	35.0	33.7	36.6	34.3			
	28	32.8	39.3	35.2	35.6	35.7			
	42	35.8	35.1	36.3	41.1	36.8			
	Mean‡	**33.1b**	**35.3ab**	**34.5ab**	**37.9a**				
3	0	45.9	48.8	56.1	59.6	52.6	0.12	0.14	0.67
	14	43.2	54.3	44.3	50.5	48.1			
	28	39.1	49.2	50.2	45.5	46			
	42	52.1	49.5	55.3	56.9	53.5			
	Mean‡	45.1	50.4	51.5	53.1				
4	0	21.0	30.5	40.4	35.0	**31.1b**	*	***	0.37
	14	28.9	34.7	36.6	42.5	**35.7ab**			
	28	33.2	36.7	40.8	38.6	**37.3a**			
	42	35.1	35.9	37.0	38.4	**36.6a**			
	Mean‡	**29.6b**	**34.5ab**	**38.6a**	**38.6a**				

† Denotes significance at the 0.05 (*), 0.01 (**), 0.001 (***) probability level. Effects are conprered significant at $P \leq 0.10$.

‡ Numbers within same row or column followed by same letter are not significant at $P \leq 0.10$.

Table 7. Summary of average NDVI readings taken at V5-8 with a Greenseeker Model 505 for combinations of at planting (AP) and in-season (IS) S rates at four locations in Minnesota. Treatment mean values are summarized for the AP and IS treatments.

Site	AP S rate	IS S Rate (kg S ha^{-1})					Statistics†		
		0	14	28	42	Mean‡	AP	IS	AP x IS
	kg ha^{-1}						----------*P*>F-----------		
1	0	0.78	0.78	0.761	0.759	0.771	0.15	0.91	0.84
	14	0.776	0.793	0.796	0.797	0.791			
	28	0.792	0.778	0.788	0.787	0.786			
	42	0.793	0.803	0.793	0.781	0.793			
	Mean‡	0.786	0.789	0.786	0.783				
2	0	0.852	0.87	0.871	0.864	0.865	0.12	0.75	0.25
	14	0.863	0.85	0.857	0.853	0.855			
	28	0.867	0.858	0.857	0.859	0.86			
	42	0.861	0.863	0.863	0.855	0.861			
	Mean‡	0.861	0.86	0.862	0.858				
3	0	0.841	0.836	0.833	0.841	0.838	0.61	0.71	0.76
	14	0.839	0.833	0.84	0.841	0.838			
	28	0.835	0.842	0.831	0.811	0.830			
	42	0.829	0.835	0.841	0.825	0.833			
	Mean‡	0.836	0.836	0.836	0.829				
4	0	0.847	0.839	0.838	0.847	**0.843b**	**	0.85	0.99
	14	0.851	0.864	0.856	0.851	**0.856ab**			
	28	0.871	0.872	0.861	0.874	**0.869a**			
	42	0.878	0.871	0.871	0.891	**0.877a**			
	Mean‡	0.861	0.862	0.857	0.864				

† Denotes significance at the 0.05 (*), 0.01 (**), 0.001 (***) probability level. Effects are considered significant at $P \leq 0.10$.

‡ Numbers within same row or column followed by same letter are not significant at $P \leq 0.10$.

Table 8. Summary of average R2 ear leaf S concentrations for combinations of at planting (AP) and in-season (IS) S rates at four locations in Minnesota. Treatment mean values are summarized for the AP and IS treatments.

Site	AP S rate	IS S Rate (kg S ha^{-1})					Statistics†		
		0	14	28	42	Mean‡	AP	IS	AP x IS
	kg ha^{-1}	---------------g S kg^{-1}----------------					---------*P*>F-------		
1	0	3.0	2.7	2.7	2.7	2.8	0.32	0.50	0.99
	14	3.0	2.9	2.8	2.9	2.9			
	28	2.9	3.0	2.9	2.9	2.9			
	42	2.8	2.9	2.8	2.8	2.8			
	Mean‡	2.9	2.9	2.8	2.8				
2	0	2.5	2.5	2.6	2.7	**2.6ab**	*	**	0.96
	14	2.4	2.5	2.6	2.8	**2.5b**			
	28	2.5	2.5	2.7	2.9	**2.6ab**			
	42	2.5	2.8	2.9	3.0	**2.8a**			
	Mean‡	**2.5b**	**2.6b**	**2.7ab**	**2.9a**				
3	0	2.3	2.4	2.6	2.4	**2.4ab**	0.07	*	0.45
	14	2.3	2.4	2.4	2.5	**2.3b**			
	28	2.5	2.4	2.5	2.5	**2.5ab**			
	42	2.5	2.4	2.5	2.7	**2.5ab**			
	Mean‡	**2.4b**	**2.4ab**	**2.5ab**	**2.5a**				
4	0	2.2	2.5	2.6	2.7	2.5	0.83	**	0.23
	14	2.5	2.3	2.4	2.6	2.5			
	28	2.3	2.6	2.4	2.6	2.5			
	42	2.5	2.4	2.3	2.5	2.4			
	Mean‡	**2.4b**	**2.4b**	**2.5b**	**2.6a**				

† Denotes significance at the 0.05 (*), 0.01 (**), 0.001 (***) probability level. Effects are considered significant at $P \leq 0.10$.

‡ Numbers within same row or column followed by same letter are not significant at $P \leq 0.10$.

Table 9. Summary of average N to S R2 ear leaf concentration ratios for combinations of at planting (AP) and in-season (IS) S rates at four locations in Minnesota. Treatment mean values are summarized for the AP and IS treatments.

Site	AP S rate	IS S Rate (kg S ha^{-1})					Statistics†		
		0	14	28	42	Mean‡	AP	IS	AP x IS
	kg ha^{-1}						----------*P*>F----------		
1	0	9.3	10.0	10.5	10.3	10.1	0.64	0.26	0.99
	14	9.4	9.8	10.0	9.4	9.6			
	28	9.6	9.8	10.2	10.0	9.9			
	42	9.8	9.6	10.3	10.3	10.0			
	Mean‡	9.6	9.8	10.2	10.0				
2	0	12.4	11.6	11.3	11.0	11.6	0.12	**	0.91
	14	12.3	11.9	11.2	10.6	11.5			
	28	11.3	11.8	11.2	9.7	11.0			
	42	11.8	10.9	9.9	10.0	10.7			
	Mean‡	**11.9a**	**11.6ab**	**10.9bc**	**10.3c**				
3	0	11.7	12.6	11.3	11.5	11.8	0.43	0.55	0.80
	14	12.6	12.5	12.2	12.2	12.4			
	28	11.8	12.4	12.2	12.7	12.3			
	42	12.8	12.3	12.0	11.7	12.2			
	Mean‡	12.2	12.4	11.9	12.0				
4	0	12.6	12.4	11.7	11.3	**12.0a**	**	***	0.51
	14	12.5	12.5	12.1	10.7	**11.9ab**			
	28	12.6	12.3	11.9	10.4	**12.1a**			
	42	11.9	12.3	11.3	10.5	**11.5b**			
	Mean‡	**12.4a**	**12.4a**	**11.7b**	**10.9c**				

† Denotes significance at the 0.05 (*), 0.01 (**), 0.001 (***) probability level. Effects are considered significant at $P \leq 0.10$.
‡ Numbers within same row or column followed by same letter are not significant at $P \leq 0.10$.

Table 10. Summary of average SPAD readings at the R2 growth stage for combinations of at planting (AP) and in-season (IS) S rates at four locations in Minnesota. Treatment mean values are summarized for the AP and IS treatments.

Site	AP S rate	IS S Rate (kg S ha^{-1})					Statistics†		
		0	14	28	42	Mean	AP	IS	AP x IS
	kg ha^{-1}						------------*P*>F------------		
1	0	59.4	60.3	59.7	60.5	60.0	0.98	0.92	0.99
	14	60.2	59.9	60.4	61.4	60.4			
	28	58.6	59.8	60.9	60.9	60.0			
	42	60.9	60.3	60.0	59.7	60.2			
	Mean‡	59.8	60.1	60.2	60.5				
2	0	54.0	52.9	54.2	52.7	53.4	0.94	0.98	0.99
	14	53.3	53.9	52.7	54.4	53.6			
	28	54.0	53.1	54.4	53.6	53.8			
	42	54.3	54.1	53.6	54.2	54.0			
	Mean‡	53.9	53.5	53.7	53.7				
3	0	58.5	58.4	58.1	57.9	58.2	0.91	0.64	0.66
	14	58.0	59.2	58.5	57.7	58.3			
	28	57.6	58.1	57.5	59.2	58.0			
	42	58.7	58.8	56.4	57.6	57.9			
	Mean‡	58.2	58.6	57.5	58.1				
4	0	55.1	55.5	56.9	57.0	56.4	0.31	*	0.49
	14	55.5	56.1	58.0	57.2	56.6			
	28	54.9	55.9	55.7	56.6	55.8			
	42	56.8	56.5	55.8	57.4	56.6			
	Mean‡	**55.6b**	**56b**	**56.5ab**	**57.2a**				

† Denotes significance at the 0.05 (*), 0.01 (**), 0.001 (***) probability level. Effects are considered significant at $P \leq 0.10$.

‡ Numbers within same row or column followed by same letter are not significant at $P \leq 0.10$.

Table 11. Summary of average SPAD readings at the R4 growth stage for combinations of at planting (AP) and in-season (IS) S rates at four locations in Minnesota. Treatment mean values are summarized for the AP and IS treatments.

Site	AP S rate	IS S Rate (kg S ha^{-1})					Statistics†		
		0	14	28	42	Mean‡	AP	IS	AP x IS
	kg ha^{-1}						----------*P*>F-----------		
1	0	60.5	58.8	59.9	60.3	59.8	0.62	0.41	0.47
	14	59.8	60.7	60.1	61.7	60.6			
	28	59.3	62.4	60.7	60.1	60.5			
	42	59.0	58.7	60.8	61.1	59.8			
	Mean‡	59.3	60.0	60.3	60.9				
2	0	56.3	55.0	56.8	55.9	56.0	0.67	0.32	1.00
	14	55.4	55.1	56.7	54.5	55.4			
	28	57.1	56.1	56.9	55.9	56.5			
	42	56.2	55.1	56.5	55.1	55.7			
	Mean‡	56.2	55.3	56.7	55.3				
3	0	57.7	58.8	57.2	58.1	57.9	0.83	0.96	0.99
	14	58.1	57.3	58.0	58.1	57.9			
	28	57.7	56.9	57.6	57.6	57.4			
	42	57.7	57.7	56.8	57.0	57.4			
	Mean‡	57.8	57.7	57.4	57.7				
4	0	55.0	56.2	57.6	57.5	56.6	0.75	**	0.42
	14	56.5	56.4	57.7	57.1	56.9			
	28	56.0	56.3	57.2	58.3	57.0			
	42	55.1	57.2	55.1	58.3	56.4			
	Mean‡	**55.6b**	**56.5ab**	**56.9ab**	**57.8a**				

† Denotes significance at the 0.05 (*), 0.01 (**), 0.001 (***) probability level. Effects are considered significant at $P \leq 0.10$.

‡ Numbers within same row or column followed by same letter are not significant at $P \leq 0.10$.

Table 12. Summary of average grain yield for combinations of at plant (AP) and in-season (IS) S rates at four locations in Minnesota. Treatment mean values are summarized for the AP and IS treatments.

Site	AP S rate	IS S Rate (kg S ha^{-1})					Statistics†		
		0	14	28	42	Mean‡	AP	IS	AP x IS
	kg ha^{-1}	---------------------Mg ha^{-1}-------------------					---------*P*>F----------		
1	0	13.0	13.5	12.9	1.4	13.2	0.83	0.35	0.51
	14	13.2	13.3	13.6	13.3	13.3			
	28	13.0	12.9	13.5	13.3	13.2			
	42	13.1	13.1	13.1	13.7	13.2			
	Mean‡	13.1	13.2	13.3	13.4				
2	0	15.5	15.3	15.3	15.1	15.3	0.49	0.97	0.11
	14	15.5	14.4	15.0	15.2	15.0			
	28	14.8	15.4	15.2	14.8	15.1			
	42	15.1	15.6	15.1	15.3	15.3			
	Mean‡	15.2	15.2	15.2	15.1				
3	0	11.8	13.1	12.4	11.6	12.2	0.99	0.37	0.40
	14	12.2	12.1	11.8	13.1	12.2			
	28	12.0	12.4	12.2	12.1	12.2			
	42	12.2	12.4	12.5	11.0	12.1			
	Mean‡	12.0	12.5	12.3	11.9				
4	0	11.7	10.5	11.1	10.7	11.0	0.25	0.77	0.98
	14	11.4	10.8	11.4	11.6	11.3			
	28	11.1	10.3	10.6	11.1	10.8			
	42	10.1	10.5	10.1	10.4	10.3			
	Mean‡	11.1	10.5	10.8	10.9				

† Denotes significance at the 0.05 (*), 0.01 (**), 0.001 (***) probability level. Effects are considered significant at $P \leq 0.10$.

‡ Numbers within same row or column followed by same letter are not significant at $P \leq 0.10$.

Table 13. Summary of average grain S concentrations for combinations of at planting (AP) and in-season (IS) S rates at four locations in Minnesota. Treatment mean values are summarized for the AP and IS treatments.

Site	AP S rate	IS S Rate (kg S ha^{-1})					Statistics†		
		0	14	28	42	Mean‡	AP	IS	AP x IS
	kg ha^{-1}	---------------g kg^{-1}-------------					----------*P*>F----------		
1	0	1.34	1.11	1.10	1.25	1.20	0.32	0.54	0.60
	14	1.12	1.12	1.08	1.10	1.10			
	28	1.15	1.16	1.20	1.13	1.16			
	42	1.13	1.09	1.15	1.21	1.14			
	Mean‡	1.19	1.12	1.13	1.17				
2	0	1.31	1.21	1.34	1.14	1.25	0.33	0.24	0.36
	14	1.27	1.21	1.38	1.26	1.28			
	28	1.23	1.24	1.23	1.17	1.22			
	42	1.28	1.37	1.24	1.28	1.29			
	Mean‡	1.27	1.25	1.30	1.21				
3	0	1.13	1.17	1.14	1.18	1.15	0.15	0.50	0.57
	14	1.16	1.08	1.12	1.23	1.15			
	28	1.20	1.18	1.21	1.26	1.21			
	42	1.16	1.18	1.14	1.11	1.15			
	Mean‡	1.16	1.15	1.15	1.19				
4	0	1.10	1.21	1.27	1.18	1.19	0.86	0.53	0.66
	14	1.19	1.08	1.32	1.45	1.19			
	28	1.21	1.17	1.35	1.15	1.22			
	42	1.32	1.20	1.16	1.28	1.24			
	Mean‡	1.20	1.16	1.27	1.26				

† Denotes significance at the 0.05 (*), 0.01 (**), 0.001 (***) probability level. Effects are considered significant at $P \leq 0.10$.

‡ Numbers within same row or column followed by same letter are not significant at $P \leq 0.10$.

Table 14. Summary of average S removal of grain for combinations of at planting (AP) and in-season (IS) S rates at four locations in Minnesota. Treatment mean values are summarized for the AP and IS treatments.

Site	AP S rate	IS S Rate (kg S ha^{-1})					Statistics†		
		0	14	28	42	Mean‡	AP	IS	AP x IS
	kg ha^{-1}	-----------------kg ha^{-1}----------------					----------*P*>F-----------		
1	0	13.1	11.3	10.7	11.3	11.6	0.73	0.70	0.23
	14	11.2	11.2	11.1	11.0	11.1			
	28	11.3	11.2	12.2	10.8	11.4			
	42	11.1	10.8	11.3	12.4	11.4			
	Mean‡	11.8	11.1	11.3	11.4				
2	0	14.3	13.6	14.3	14.5	14.2	0.34	0.89	0.57
	14	15.3	13.3	13.9	14.0	14.2			
	28	13.7	14.4	14.4	14.2	14.2			
	42	15.3	16.3	14.3	14.3	15.1			
	Mean‡	14.7	14.4	14.2	14.3				
3	0	10.5	11.3	10.8	10.2	10.7	0.26	0.64	0.37
	14	10.9	10.0	7.9	11.2	10.0			
	28	11.0	11.0	11.2	11.6	11.2			
	42	10.0	11.3	11.0	10.4	10.7			
	Mean‡	10.6	10.9	10.2	10.9				
4	0	9.6	9.6	11.4	9.5	10.0	0.46	0.65	0.93
	14	10.4	9.9	11.7	12.5	11.1			
	28	10.1	9.2	10.9	9.7	10.0			
	42	10.2	9.7	9.0	10.0	9.7			
	Mean‡	10.1	9.6	10.7	10.4				

† Denotes significance at the 0.05 (*), 0.01 (**), 0.001 (***) probability level. Effects are considered significant at $P \leq 0.10$.
‡ Numbers within same row or column followed by same letter are not significant at $P \leq 0.10$.

Table 15. Summary of average grain moisture concentration for combinations of at planting (AP) and in-season (IS) S rates at four locations in Minnesota. Treatment mean values are summarized for the AP and IS treatments.

Site	AP S rate	IS S Rate (kg S ha^{-1})					Statistics†		
		0	14	28	42	Mean‡	AP	IS	AP x IS
	kg ha^{-1}	--------------- g kg^{-1}--------------					---------*P*>F---------		
1	0	147	153	155	150	151	0.65	0.77	0.73
	14	152	151	150	151	151			
	28	152	151	150	151	149			
	42	152	147	149	151	150			
	Mean‡	150	149	151	151				
2	0	236	243	239	235	238	0.73	0.52	0.87
	14	235	229	243	228	233			
	28	235	239	235	234	236			
	42	242	232	236	229	234			
	Mean‡	237	236	238	231				
3	0	118	110	109	110	112	0.78	0.33	0.42
	14	115	115	100	111	113			
	28	113	112	112	110	112			
	42	110	117	114	114	114			
	Mean‡	114	114	111	111				
4	0	130	133	135	132	133	0.45	0.51	0.89
	14	133	133	135	131	133			
	28	131	131	132	131	131			
	42	132	133	130	131	132			
	Mean‡	132	124	133	131				

† Denotes significance at the 0.05 (*), 0.01 (**), 0.001 (***) probability level. Effects are considered significant at $P \leq 0.10$.
‡ Numbers within same row or column followed by same letter are not significant at $P \leq 0.10$.

Table 16. Irrigator well water SO42--S concentrations and total application.

Site	Water Concentration	Water Application	Total S Applied
	---mg S kg^{-1}---	---cm^{3}---	---kg S ha^{-1}---
1	14.56	539.7	7.9
2	20.72	822.4	17.0
3	14.00	616.8	8.6
4	8.74	1644.0	14.4

Table 17. Monthly total precipitation data for all sites in S studies. Data are collected from the nearest weather station.

	Precipitation Data (mm)							
	Site 1		Site 2		Site 3		Site 4	
month	total	DN†	total	DN	total	DN	total	DN
April	27.5	-2	27.5	0.9	39.1	9.6	26	0.3
May	34.4	-2.1	34.4	-1.2	62.5	26	87.6	58.1
June	57.5	15.8	57.5	14	151.1	109.4	23.6	-18.1
July	39.9	-3.5	39.9	0.3	39.9	-3.5	35.9	2.8
August	18.6	-23.4	18.6	-27.4	NA	NA	12.2	-25.7
September	8.4	-24.5	8.4	-24.7	7.3	-25.6	2.4	-32.2

†DN, departure from 30 year normal.

Table 18. Summary of mono-calcium phosphate extractable SO_4^{2-}-S from samples collected to 75 cm sampled in 15 cm depth increments for selected sulfur rate treatments at four locations in Minnesota.

		AP and IS Fertilizer Rate				Statistics†						
		0		42								
Site	Depth‡	0	42	0	42	AP	IS§	AP x IS	Depth	Depth x AP	Depth x IS	Depth x AP x IS
	cm	g kg^{-1}				----------------------------------*P*>F-----------------------------------						
1	0-15	6.8	6.3	7.0	8.0	0.10	0.32	0.53	0.35	0.23	0.31	0.80
	15-30	6.8	4.5	6.0	8.3							
	30-45	6.0b	5.8b	10.5a	11a							
	45-60	4.8	8.0	5.0	9.0							
	60-75	5.8	7.8	7.3	9.0							
2	0-15	6.8	9.5	11.5	13.3	*	*	0.53	*	0.57	0.27	0.55
	15-30	4.75c	10.5b	9b	15.5a							
	30-45	4.8c	6.7b	8.3b	14a							
	45-60	5.5	6.0	6.5	9.7							
	60-75	12.0	7.0	---	8.0							
3	0-15	4.0	5.0	4.8	4.5	0.22	0.63	0.52	*	0.37	0.98	0.59
	15-30	4.5	6.0	5.3	4.8							
	30-45	5.0	5.5	6.0	5.5							
	45-60	5.3	4.8	5.5	6.0							
	60-75	2.7	3.5	5.3	4.5							
4	0-15	3.5b	3.5b	4.3b	7.3a	***	***	**	0.79	0.92	0.71	0.81
	15-30	3.0	3.8	4.5	5.5							
	30-45	2.3c	3.3b	3.3b	7.0a							
	45-60	2.8c	4.3b	3.3c	7.0a							
	60-75	3.7	3.0	3.0	6.0							

† Denotes significance at the 0.05 (*), 0.01 (**), 0.001 (***) probability level. Effects are considered significant at $P \leq 0.10$.
‡ Numbers within same row followed by same letter are not significant at $P \leq 0.10$.
§In-season (IS), at planting (AP)

Table 19. Site chemical soil test characteristic for composite samples collected at 0-15, 15-30, and 30-60 cm prior to potassium fertilizer application.

		Soil Test 0-15 cm†			NH_4OAC-K		
Site	**Depth**	**pH**	**OM**	**P**	**mean**	**st dev**	**Total K**
	cm		g kg^{-1}		-----mg kg^{-1}-----		
1	0-15	5.4	11	15	42	8.7	438
	15-30	---	---	---	41	---	414
	30-60	---	---	---	35	---	273
2	0-15	5.5	39	37	90	14.7	1172
	15-30	---	---	---	56	---	727
	30-60	---	---	---	55	---	803
3	0-15	6.9	13	25	60	11	219
	15-30	---	---	---	36	---	136
	30-60	---	---	---	29	---	108
4	0-15	6.8	19	109	157	34.4	625
	15-30	---	---	---	47	---	283
	30-60	---	---	---	37	---	128

† P, Bray-P1 phosphorus; pH, soil pH 1:1 soil:water; OM, LOI organic matter; soil test K, and Total K.

ǂ(LS) loamy sand and (SL) sandy loam.

Table 20. Potassium studies cation exchange capacity (CEC) and soil particle size.

Site	Depth	CEC	Particle Size		
			Sand	Silt	Clay
	cm	$cmol_c\ kg^{-1}$	----------g kg^{-1}----------		
1	0-15	5.03	897	27	77
	15-30	6.0	893	13	93
	30-45	5.4	880	19	101
	45-60	3.6	908	12	80
	60-75	3.9	893	24	83
2	0-15	14.3	629	200	171
	15-30	14.2	672	142	186
	30-45	8.0	837	61	102
	45-60	6.1	890	22	85
	60-75	3.3	892	25	83
3	0-15	4.5	861	41	98
	15-30	5.6	878	39	83
	30-45	4.5	815	102	83
	45-60	3.4	862	54	83
	60-75	3.4	915	18	67
4	0-15	7.4	809	70	122
	15-30	8.8	789	65	146
	30-45	7.3	810	80	107
	45-60	5.5	810	75	115
	60-75	4.4	882	23	95

Table 21. Summary of average V5-8 plant weights for combinations of at planting (AP) and in-season (IS) K rates at four locations in Minnesota. Treatment mean values are summarized for the AP and IS treatments.

Site	AP K rate	IS K Rate (kg K ha^{-1})					Statistics†		
		0	72	143	215	Mean‡	AP	IS	AP x IS
	kg ha^{-1}	--------g plant^{-1}-------					----------*P*>F----------		
1	0	1.9	1.8	2.0	2.0	1.9	0.11	0.96	0.79
	72	1.9	1.8	1.8	1.8	1.8			
	143	2.6	2.5	2.1	2.6	2.4			
	215	2.0	2.0	3.0	1.9	2.2			
	Mean ‡	2.1	2.0	2.2	2.0				
2	0	10.8	10.0	8.9	9.7	9.9	0.23	0.93	0.53
	72	10.4	10.2	9.6	10.8	10.2			
	143	10.6	9.8	10.2	11.0	10.4			
	215	10.6	11.9	11.8	10.0	11.1			
	Mean ‡	10.6	10.5	10.1	10.4				
3	0	10.3	10.4	11.6	11.3	10.9	0.64	0.15	0.73
	72	10.7	13.2	10.6	9.2	10.9			
	143	11.0	11.8	10.8	10.0	10.9			
	215	12.7	13.6	11.3	9.8	11.9			
	Mean ‡	11.2	12.2	11.1	10.1				
4	0	18.3	18.8	19.1	17.9	18.5	0.74	0.63	0.87
	72	18.3	19.3	19.3	18.8	18.9			
	143	18.4	18.3	17.4	18.4	18.1			
	215	19.3	19.1	19.5	17.0	18.7			
	Mean ‡	18.6	18.9	18.8	18.0				

† Denotes significance at the 0.05 (*), 0.01 (**), 0.001 (***) probability level. Effects are considered significant at $P \leq 0.10$.
‡ Numbers within same row or column followed by same letter are not significant at $P \leq 0.10$.

Table 22. Summary of average V5-8 plant K concentrations for combinations of at planting (AP) and in-season (IS) K rates at four locations in Minnesota. Treatment mean values are summarized for the AP and IS treatments.

Site	AP K rate	IS K Rate (kg K ha^{-1})					Statistics†		
		0	72	143	215	Mean‡	AP	IS	AP x IS
	kg ha^{-1}	-------------g kg^{-1}-----------					----------*P*>F--------		
1	0	24.1	26.7	26.2	26.9	**25.9c**	***	0.47	0.64
	72	34.6	34.2	34.8	37.3	**35.2b**			
	143	35.7	36.7	36.7	36.7	**36.4b**			
	215	38.8	38.4	39.5	37.4	**38.5a**			
	Mean‡	33.3	34.5	34.8	34.6				
2	0	38.5	46.6	13.3	49.8	**44.5b**	***	**	0.24
	72	48.1	54.6	47.2	54.2	**54.7a**			
	143	49.9	53.8	56.9	58.3	**51.0a**			
	215	54.0	53.5	58.2	54.0	**54.9a**			
	Mean‡	**47.6b**	**52.1a**	**51.4ab**	**54.1a**				
3	0	19.3	27.8	29.6	30.3	**26.7c**	***	***	*
	72	29.5	32.5	32.9	36.6	**32.8b**			
	143	30.8	32.1	36.5	38.1	**34.4b**			
	215	34.5	37.8	39.1	39.7	**38.2a**			
	Mean‡	**28.5c**	**33b**	**34.5ab**	**36.2a**				
4	0	41.9	46.1	40.5	49.7	45.5	0.59	**	*
	72	44.4	46.5	48.2	47.6	46.7			
	143	43.3	40.8	49.6	44.6	44.6			
	215	37.1	47.0	46.5	51.4	45.5			
	Mean‡	**48.3b**	**46.2ab**	**45.1a**	**41.7a**				

† Denotes significance at the 0.05 (*), 0.01 (**), 0.001 (***) probability level. Effects are considered significant at $P \leq 0.10$.

‡ Numbers within same row or column followed by same letter are not significant at $P \leq 0.10$.

Table 23. Summary of average V5-8 plant K uptake for combinations of at planting (AP) and in-season (IS) K rates at four locations in Minnesota. Treatment mean values are summarized for the AP and IS treatments.

Site	AP K rate	IS K Rate (kg K ha^{-1})					Statistics†		
		0	72	143	215	Mean‡	AP	IS	AP x IS
	kg ha^{-1}	--------------mg K plant^{-1}---------------					------------*P*>F-------------		
1	0	45	45	47	52	**47c**	***	0.99	0.99
	72	65	62	63	67	**64bc**			
	143	90	89	76	94	**87a**			
	215	78	79	85	71	**77ab**			
	Mean‡	70	69	67	71				
2	0	456	469	464	484	**468b**	*	0.68	0.59
	72	503	617	448	552	**529ab**			
	143	531	532	580	567	**552a**			
	215	570	642	683	532	**607a**			
	Mean‡	515	565	544	530				
3	0	198	288	344	345	**294c**	***	*	0.38
	72	317	429	349	340	**359bc**			
	143	339	378	393	381	**373b**			
	215	441	537	442	392	**453a**			
	Mean‡	**323b**	**408a**	**364ab**	**323ab**				
4	0	764	860	773	885	820	0.56	0.13	0.64
	72	808	882	861	891	861			
	143	800	745	863	816	806			
	215	717	898	905	875	849			
	Mean‡	772	846	851	867				

† Denotes significance at the 0.05 (*), 0.01 (**), 0.001 (***) probability level. Effects are considered significant at $P \leq 0.10$.

‡ Numbers within same row or column followed by same letter are not significant at $P \leq 0.10$.

Table 24. Summary of average NDVI readings taken at V5-8 with Greenseeker model 505 for combinations of at planting (AP) and in-season (IS) K rates at four locations in Minnesota. Treatment mean values are summarized for the AP and IS treatments.

Site	AP K rate	IS K Rate (kg K ha^{-1})					Statistics†		
		0	72	143	215	Mean‡	AP	IS	AP x IS
	kg ha^{-1}						------------*P*>F------------		
1	0	0.772	0.707	0.732	0.707	0.727	0.37	0.92	0.95
	72	0.731	0.73	0.705	0.721	0.722			
	143	0.772	0.781	0.729	0.797	0.770			
	215	0.734	0.741	0.757	0.71	0.736			
	Mean‡	0.751	0.74	0.731	0.734				
2	0	0.852	0.87	0.871	0.864	**0.865a**	0.06	0.81	0.46
	72	0.855	0.85	0.857	0.853	**0.854b**			
	143	0.867	0.858	0.857	0.859	**0.86ab**			
	215	0.861	0.863	0.863	0.855	**0.861ab**			
	Mean‡	0.859	0.86	0.862	0.858				
3	0	0.848	0.842	0.854	0.85	0.850	0.44	0.91	0.34
	72	0.851	0.85	0.854	0.855	0.852			
	143	0.857	0.838	0.835	0.849	0.844			
	215	0.851	0.866	0.856	0.839	0.853			
	Mean‡	0.852	0.85	0.851	0.848				
4	0	0.883	0.889	0.886	0.885	0.889	0.11	0.61	0.90
	72	0.896	0.889	0.888	0.89	0.887			
	143	0.886	0.88	0.881	0.884	0.885			
	215	0.891	0.893	0.886	0.89	0.887			
	Mean‡	0.851	0.862	0.857	0.854				

† Denotes significance at the 0.05 (*), 0.01 (**), 0.001 (***) probability level. Effects are considered significant at $P \leq 0.10$.
‡ Numbers within same row or column followed by same letter are not significant at $P \leq 0.10$.

Table 25. Summary of average R2 ear leaf K concentrations for combinations of at planting (AP) and in-season (IS) K rates at four locations in Minnesota. Treatment mean values are summarized for the AP and IS treatments.

Site	AP K rate	IS K Rate (kg K ha^{-1})					Statistics†		
		0	72	143	215	Mean‡	AP	IS	AP x IS
	kg ha^{-1}	---------------g K kg^{-1}------------					------------*P*>F------------		
1	0	14.8	17.8	17.7	19.7	**17.7c**	***	***	0.09
	72	18.8	20.2	21.1	21.2	**20.3b**			
	143	20.5	21.3	21.0	21.1	**21.0ba**			
	215	20.7	21.3	21.8	22.5	**21.6a**			
	Mean‡	**18.9b**	**20.3a**	**20.4ba**	**21.1a**				
2	0	19.2	22.3	23.7	24.5	**22.4c**	***	***	*
	72	23.0	23.9	23.6	25.0	**23.9b**			
	143	24.3	24.5	26.0	26.9	**25.4a**			
	215	25.1	26.4	26.7	26.0	**26.0a**			
	Mean‡	**22.9c**	**24.2b**	**25.0ba**	**25.6a**				
3	0	12.0	17.3	18.9	19.8	**16.8c**	***	***	***
	72	17.8	18.9	19.3	21.3	**19.4b**			
	143	18.7	19.3	19.5	20.7	**19.5b**			
	215	19.9	22.2	21.0	21.6	**21.2a**			
	Mean‡	**17.0c**	**19.6b**	**19.7b**	**20.8a**				
4	0	23.2	24.3	23.6	24.1	**23.8c**	***	0.24	0.98
	72	24.5	24.9	24.2	25.2	**24.7bc**			
	143	25.3	26.0	26.2	25.6	**25.8a**			
	215	25.0	25.9	25.8	26.0	**25.7ab**			
	Mean‡	24.5	25.3	25.1	25.2				

† Denotes significance at the 0.05 (*), 0.01 (**), 0.001 (***) probability level. Effects are considered significant at $P \leq 0.10$.

‡ Numbers within same row or column followed by same letter are not significant at $P \leq 0.10$.

Table 26. Summary of average N to K ear leaf concentration ratios at R2 for combinations of at planting (AP) and in-season (IS) K rates at four locations in Minnesota. Treatment mean values are summarized for the AP and IS treatments.

Site	AP K rate	IS K Rate (kg K ha^{-1})					Statistics†		
		0	72	143	215	Mean‡	AP	IS	AP x IS
	kg ha^{-1}	---------------------N/K--------------------					-----------*P*>F----------		
1	0	2.10	1.81	1.78	1.60	**1.82a**	***	***	0.08
	72	1.74	1.56	1.52	1.48	**1.58b**			
	143	1.55	1.49	1.47	1.46	**1.49bc**			
	215	1.53	1.49	1.46	1.41	**1.47c**			
	Mean‡	**1.73a**	**1.62b**	**1.55b**	**1.5b**				
2	0	1.69	1.37	1.19	1.21	**1.35a**	***	***	***
	72	1.38	1.22	1.24	1.16	**1.25b**			
	143	1.21	1.20	1.13	1.10	**1.16c**			
	215	1.17	1.13	1.14	1.11	**1.14c**			
	Mean‡	**1.34a**	**1.23b**	**1.17bc**	**1.15c**				
3	0	2.38	1.55	1.43	1.31	**1.62a**	***	***	***
	72	1.47	1.38	1.36	1.16	**1.33b**			
	143	1.38	1.26	1.24	1.01	**1.22b**			
	215	1.26	1.18	1.24	1.18	**1.22b**			
	Mean‡	**1.58a**	**1.34b**	**1.32b**	**1.17c**				
4	0	1.37	1.33	1.36	1.29	**1.34a**	***	0.39	0.95
	72	1.31	1.26	1.36	1.27	**1.3ab**			
	143	1.24	1.20	1.18	1.21	**1.21c**			
	215	1.27	1.21	1.20	1.21	**1.23bc**			
	Mean‡	1.30	1.25	1.26	1.25				

† Denotes significance at the 0.05 (*), 0.01 (**), 0.001 (***) probability level. Effects are considered significant at $P \leq 0.10$.
‡ Numbers within same row or column followed by same letter are not significant at $P \leq 0.10$.

Table 27. Summary of average SPAD readings at the R2 growth stage for combinations of at planting (AP) and in-season (IS) K rates at four locations in Minnesota. Treatment mean values are summarized for the AP and IS treatments.

Site	AP K rate	IS K Rate (kg K ha^{-1})					Statistics†		
		0	72	143	215	Mean‡	AP	IS	AP x IS
	kg ha^{-1}						------------P>F------------		
1	0	60.6	62.3	63.1	60.7	61.7	0.99	0.72	0.61
	72	60.9	60.0	62.0	63.4	61.6			
	143	62.1	62.0	61.7	63.4	61.6			
	215	60.5	62.8	61.6	61.7	61.4			
	Mean‡	61.5	61.5	62.7	62.8				
2	0	55.8	55.3	54.1	54.0	54.8	0.43	0.78	1.00
	72	54.5	53.3	53.5	54.2	53.9			
	143	53.6	53.8	52.8	52.9	53.3			
	215	53.7	52.9	53.1	53.4	53.3			
	Mean‡	54.4	53.8	53.4	53.6				
3	0	55.7	51.4	53.1	53.0	53.2	0.16	0.67	0.37
	72	53.1	51.3	54.8	50.3	52.7			
	143	51.4	52.2	52.2	51.3	51.8			
	215	51.1	52.8	50.6	50.7	51.3			
	Mean‡	52.6	51.9	52.6	51.7				
4	0	57.6	57.5	57.2	57.8	**57.5a**	*	0.42	0.75
	72	58.4	58.3	57.2	55.6	**57.7a**			
	143	56.8	55.7	57.0	55.7	**56.3b**			
	215	57.3	56.7	57.0	56.7	**56.9ab**			
	Mean‡	57.5	57.0	57.1	56.7				

† Denotes significance at the 0.05 (*), 0.01 (**), 0.001 (***) probability level. Effects are considered significant at $P \leq 0.10$.
‡ Numbers within same row or column followed by same letter are not significant at $P \leq 0.10$.

Table 28. Summary of average SPAD readings at the R4 growth stage for combinations of at planting (AP) and in-season (IS) K rates at four locations in Minnesota. Treatment mean values are summarized for the AP and IS treatments.

Site	AP K rate	IS K Rate (kg K ha^{-1})					Statistics†		
		0	72	143	215	Mean‡	AP	IS	AP x IS
	kg ha^{-1}						------------*P*>F------------		
1	0	62.1	61.9	61.1	61.5	61.6	0.83	0.91	0.99
	72	61.3	62.9	61.7	61.6	61.8			
	143	60.8	62.1	62.3	61.1	61.5			
	215	61.4	60.7	61.3	60.9	61.1			
	Mean‡	61.4	61.8	61.6	61.3				
2	0	57.4	56.0	56.6	56.2	**56.5a**	*	0.69	0.99
	72	56.9	55.1	56.4	55.3	**55.9a**			
	143	55.3	54.6	55.8	55.9	**55.4ab**			
	215	53.7	54.0	54.2	54.3	**54.0b**			
	Mean‡	55.7	54.9	55.7	55.4				
3	0	51.1	49.4	47.6	46.7	45.7	0.30	0.78	1.00
	72	49.4	47.3	48.0	47.7	48.1			
	143	46.3	44.8	43.8	44.7	44.9			
	215	46.8	48.6	46.7	47.0	47.3			
	Mean‡	48.4	47.5	46.5	46.5				
4	0	57.6	58.9	58.8	57.9	58.3	0.53	0.30	0.52
	72	57.4	57.7	57.1	56.5	57.2			
	143	59.6	57.9	57.0	56.4	57.7			
	215	58.8	56.5	58.4	57.3	57.7			
	Mean‡	58.3	57.7	57.8	57.0				

† Denotes significance at the 0.05 (*), 0.01 (**), 0.001 (***) probability level. Effects are considered significant at $P \leq 0.10$.
‡ Numbers within same row or column followed by same letter are not significant at $P \leq 0.10$.

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Table 30. Summary of average grain K concentrations for combinations of at planting (AP) and in-season (IS) K rates at four locations in Minnesota. Treatment mean values are summarized for the AP and IS treatments.

Site	AP K rate	IS K Rate (kg K ha^{-1})					Statistics†		
		0	72	143	215	Mean‡	AP	IS	AP x IS
	kg ha^{-1}	----------------g kg^{-1}---------------					------------*P*>F------------		
1	0	3.45	3.35	3.55	3.40	3.44	0.86	0.93	0.68
	72	3.55	3.33	3.58	3.55	3.50			
	143	3.35	3.65	3.53	3.50	3.51			
	215	3.58	3.63	3.58	3.63	3.60			
	Mean‡	3.48	3.49	3.52	3.56				
2	0	3.78	3.80	3.90	3.93	**3.85b**	*	0.73	0.99
	72	3.95	3.95	4.03	3.95	**3.97ab**			
	143	4.10	4.08	4.13	4.08	**4.09a**			
	215	4.00	3.88	3.95	4.05	**3.97ab**			
	Mean‡	4.00	3.90	4.00	4.00				
3	0	3.15	3.38	3.50	3.43	3.36	0.36	0.30	0.07
	72	3.40	3.40	3.50	3.53	3.46			
	143	3.40	3.45	3.35	3.53	3.43			
	215	3.55	3.35	3.50	3.33	3.44			
	Mean‡	3.37	3.39	3.46	3.46				
4	0	3.33	3.53	3.33	3.53	3.43	0.86	0.69	0.68
	72	3.45	3.40	3.43	3.40	3.42			
	143	3.48	3.55	3.48	3.38	3.47			
	215	3.55	3.35	3.25	3.45	3.40			
	Mean‡	3.45	3.46	3.37	3.44				

† Denotes significance at the 0.05 (*), 0.01 (**), 0.001 (***) probability level. Effects are considered significant at $P \leq 0.10$.
‡ Numbers within same row or column followed by same letter are not significant at $P \leq 0.10$.

Table 31. Summary of average K removal of grain for combinations of at planting (AP) and in-season (IS) K rates at four locations in Minnesota. Treatment mean values are summarized for the AP and IS treatments.

Site	AP K rate	IS K Rate (kg K ha^{-1})					Statistics†		
		0	72	143	215	Mean‡	AP	IS	AP x IS
	kg ha^{-1}	-------------------kg Ha^{-1}----------------					------------*P*>F------------		
1	0	30.4	31.9	32.3	30.7	31.3	0.24	0.20	0.83
	72	31.3	31.4	33.7	32.8	32.4			
	143	30.6	35.1	32.8	33.8	33.1			
	215	32.6	33.8	32.9	32.6	33.0			
	Mean‡	31.2	33.3	33.0	32.5				
2	0	41.6	42.5	42.6	43.6	42.6	0.35	0.86	0.75
	72	45.1	42.9	42.7	42.9	43.4			
	143	43.2	43.1	45.2	43.0	43.7			
	215	43.4	44.0	44.1	46.6	44.5			
	Mean‡	43.3	43.1	43.6	44.0				
3	0	26.3	27.7	31.7	28.6	28.6	0.66	0.97	0.91
	72	29.3	28.7	29.1	29.2	29.1			
	143	27.7	26.2	25.8	26.8	26.6			
	215	28.5	31.0	27.1	25.5	27.0			
	Mean‡	27.9	28.4	28.4	27.5				
4	0	28.3	31.6	30.3	31.2	30.3	0.72	0.95	0.96
	72	33.3	33.8	31.8	31.3	32.5			
	143	31.3	31.0	32.2	29.7	31.0			
	215	33.8	29.2	30.3	30.3	30.9			
	Mean‡	31.7	31.4	31.1	30.6				

† Denotes significance at the 0.05 (*), 0.01 (**), 0.001 (***) probability level. Effects are considered significant at $P \leq 0.10$.

‡ Numbers within same row or column followed by same letter are not significant at $P \leq 0.10$.

Table 32. Summary of average grain moisture concentration for combinations of at planting (AP) and in-season (IS) K rates at four locations in Minnesota. Treatment mean values are summarized for the AP and IS treatments.

Site	AP K rate	IS K Rate (kg K ha^{-1})					Statistics†		
		0	72	143	215	Mean‡	AP	IS	AP x IS
	kg ha^{-1}	---------------------g kg^{-1}---------------------					------------*P*>F------------		
1	0	125	129	130	136	130	0.41	0.14	0.44
	72	129	127	134	132	131			
	143	133	134	132	131	133			
	215	130	133	131	135	132			
	Mean‡	129	131	132	134				
2	0	226	242	232	238	234	0.30	0.33	0.87
	72	240	245	243	239	242			
	143	245	243	238	235	240			
	215	239	246	237	239	241			
	Mean‡	238	244	238	238				
3	0	143	137	143	139	140	0.36	0.95	0.98
	72	142	139	140	138	140			
	143	136	127	131	130	131			
	215	133	145	135	134	137			
	Mean‡	139	137	138	135				
4	0	134	131	132	129	131	0.51	0.92	0.66
	72	132	132	135	137	134			
	143	132	134	130	134	132			
	215	130	131	133	132	132			
	Mean‡	132	132	132	133				

† Denotes significance at the 0.05 (*), 0.01 (**), 0.001 (***) probability level. Effects are considered significant at $P \leq 0.10$.
‡ Numbers within same row or column followed by same letter are not significant at $P \leq 0.10$.

Table 33. Total monthly precipitation data for potassium study locations. Data are collected from the nearest weather station within 30 km of each location.

	Precipitation Data (mm)							
	Site 1		Site 2		Site 3		Site 4	
month	total	DN†	total	DN	total	DN	total	DN
April	36	5.8	27.5	0.9	17.8	-12.4	26	0.3
May	56.2	21.5	34.4	-1.2	112.7	78	87.6	58.1
June	30.9	-13.9	57.5	14	43.2	-1.6	23.6	-18.1
July	96.7	52.8	39.9	0.3	41.3	-2.6	35.9	2.8
August	32.3	-7.5	18.6	-27.4	12.4	-27.4	12.2	-25.7
September	6.1	-33.7	8.4	-24.7	2.1	-37.7	2.4	-32.2

†DN, departure from 30 year normal.

Table 34. Summary of multi-depth K soil tests (NH_4OAC-K) for plots containing lysimeters in K studies. Treatment means summarized for at planting (AP) and in-season (IS) treatments.

		Main by Sub				Statistics†						
		0		215								
Site	Depth‡	0	215	0	215	AP§	IS	AP x IS	Depth	Depth x AP	Depth x IS	Depth x AP x IS
	cm	mg kg^{-1}				----------------------------------			*P*>F		----------------------------------	
1	0-15	38c	71b	81b	108a	**	*	0.87	***	***	***	0.99
	15-30	35	48	50	61							
	30-45	29	28	36	33							
	45-60	26	27	28	30							
	60-75	28	29	27	29							
2	0-15	71	88	91	104	0.24	0.79	0.99	***	0.45	0.86	0.90
	15-30	62	57	49	54							
	30-45	45	46	33	37							
	45-60	38	41	29	25							
	60-75	---	41	26	14							
3	0-15	29c	101a	69b	123a	.*	**	0.90	***	0.42	***	0.93
	15-30	29	32	46	57							
	30-45	26	26	37	34							
	45-60	26	23	30	28							
	60-75	21	22	22	24							
4	0-15	79c	147a	122b	158a	0.34	0.10	0.58	***	*	***	0.49
	15-30	55	48	62	58							
	30-45	40	41	40	39							
	45-60	35	34	33	30							
	60-75	28	32	25	26							

† Denotes significance at the 0.05 (*), 0.01 (**), 0.001 (***) probability level. Effects are considered significant at $P \leq 0.10$.
‡ Numbers within same row followed by same letter are not significant at $P \leq 0.10$.
§In-season (IS), at planting (AP)

Figure 1. Soil pore water SO_4^{2-}-S concentration (a) for rates of 0 or 42 kg S ha^{-1} applied at planting (AP) in combination with 0 or 42 kg S ha^{-1} applied in-season (IS) and daily precipitation data (b) at Site 1. Letters indicate treatment significance within individual sampling dates.

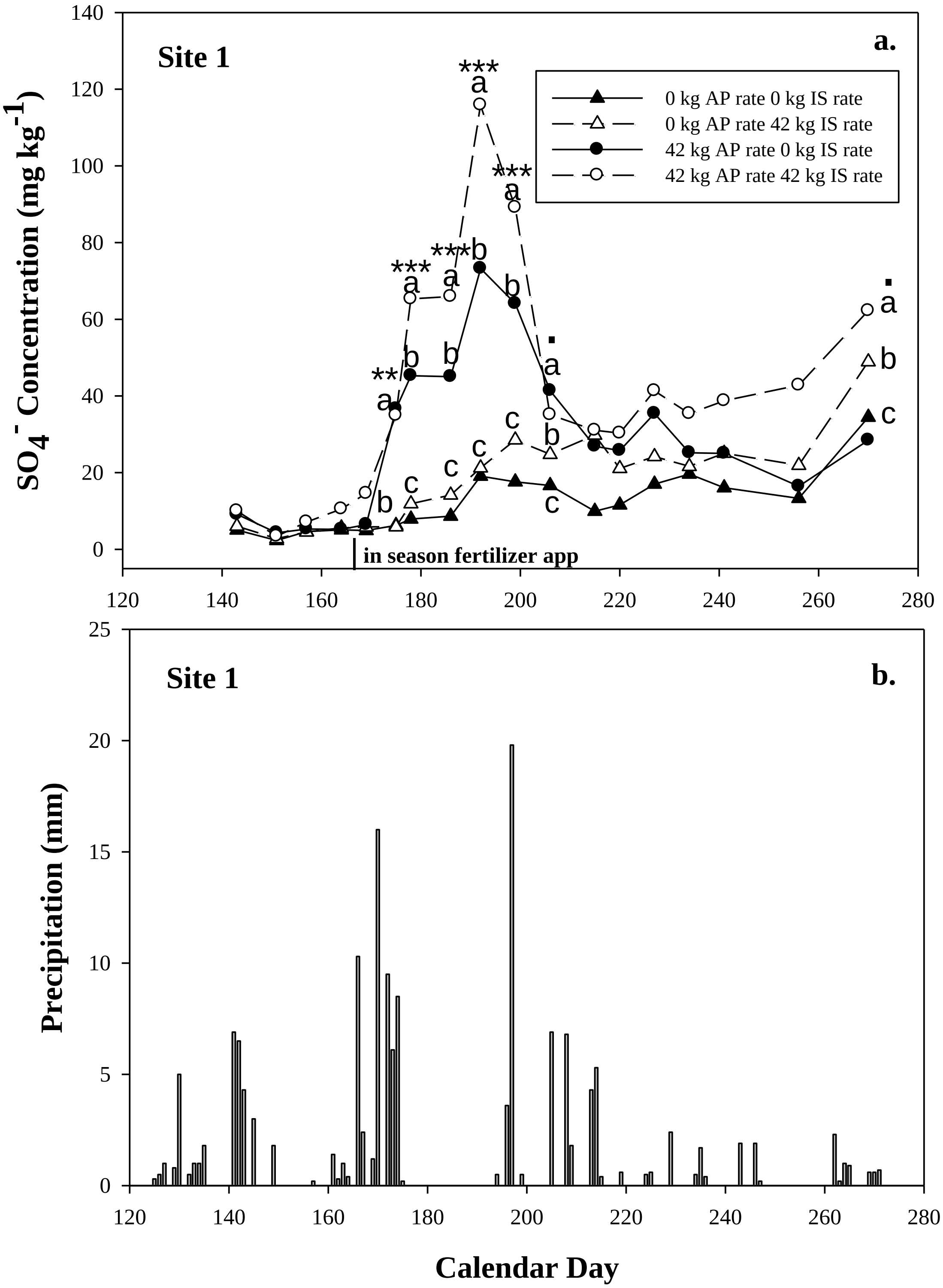


Figure 2. Soil pore water SO_4^{2-}-S concentration (a) for rates of 0 or 42 kg S ha^{-1} applied at planting (AP) in combination with 0 or 42 kg S ha^{-1} applied in-season (IS) and daily precipitation data (b) at Site 2. Letters indicate treatment significance within individual sampling dates.

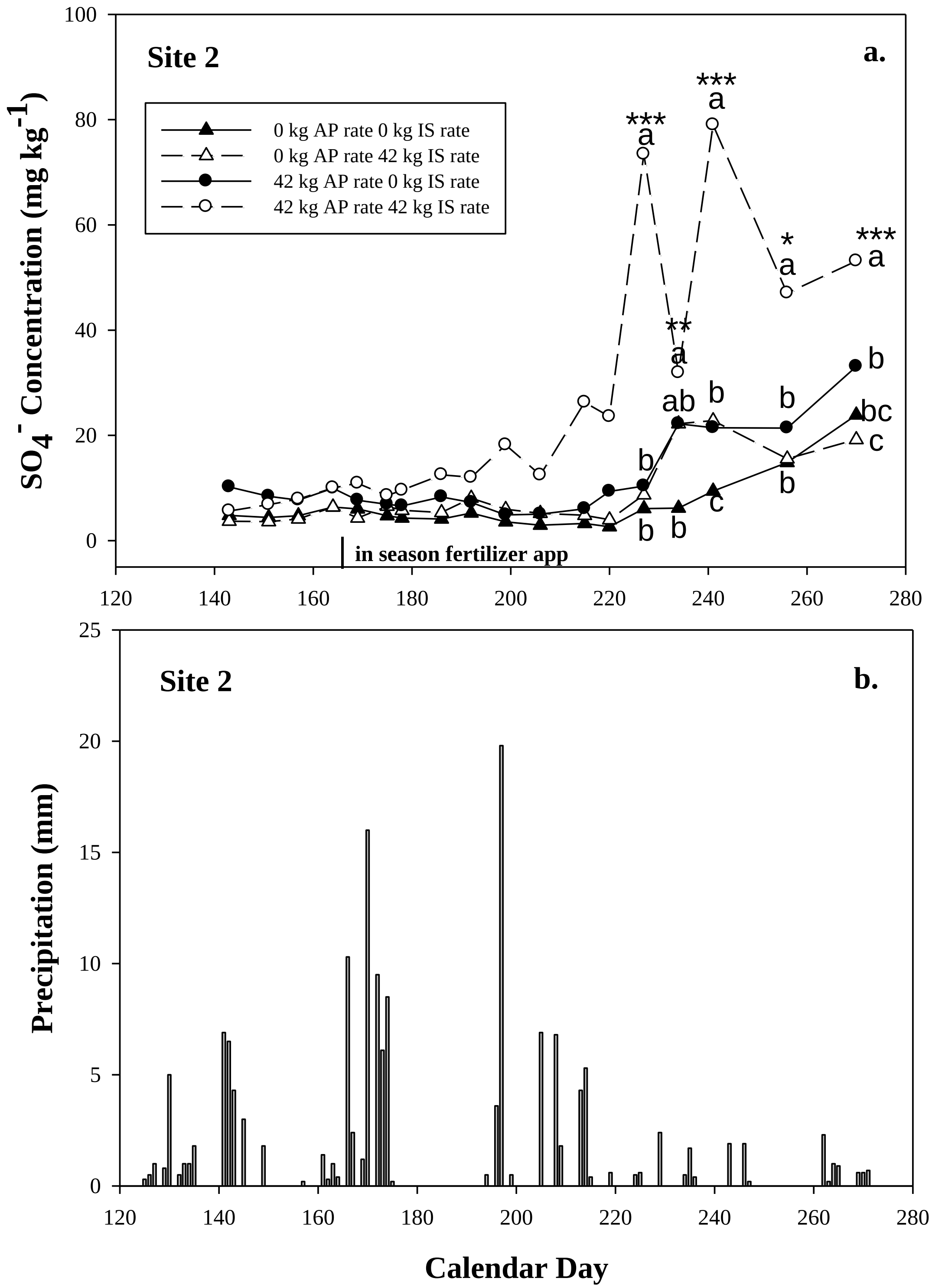


Figure 3. Soil pore water SO_4^{2-}-S concentration (a) for rates of 0 or 42 kg S ha^{-1} applied at planting (AP) in combination with 0 or 42 kg S ha^{-1} applied in-season (IS) and daily precipitation data (b) at Site 3. Letters indicate treatment significance within individual sampling dates.

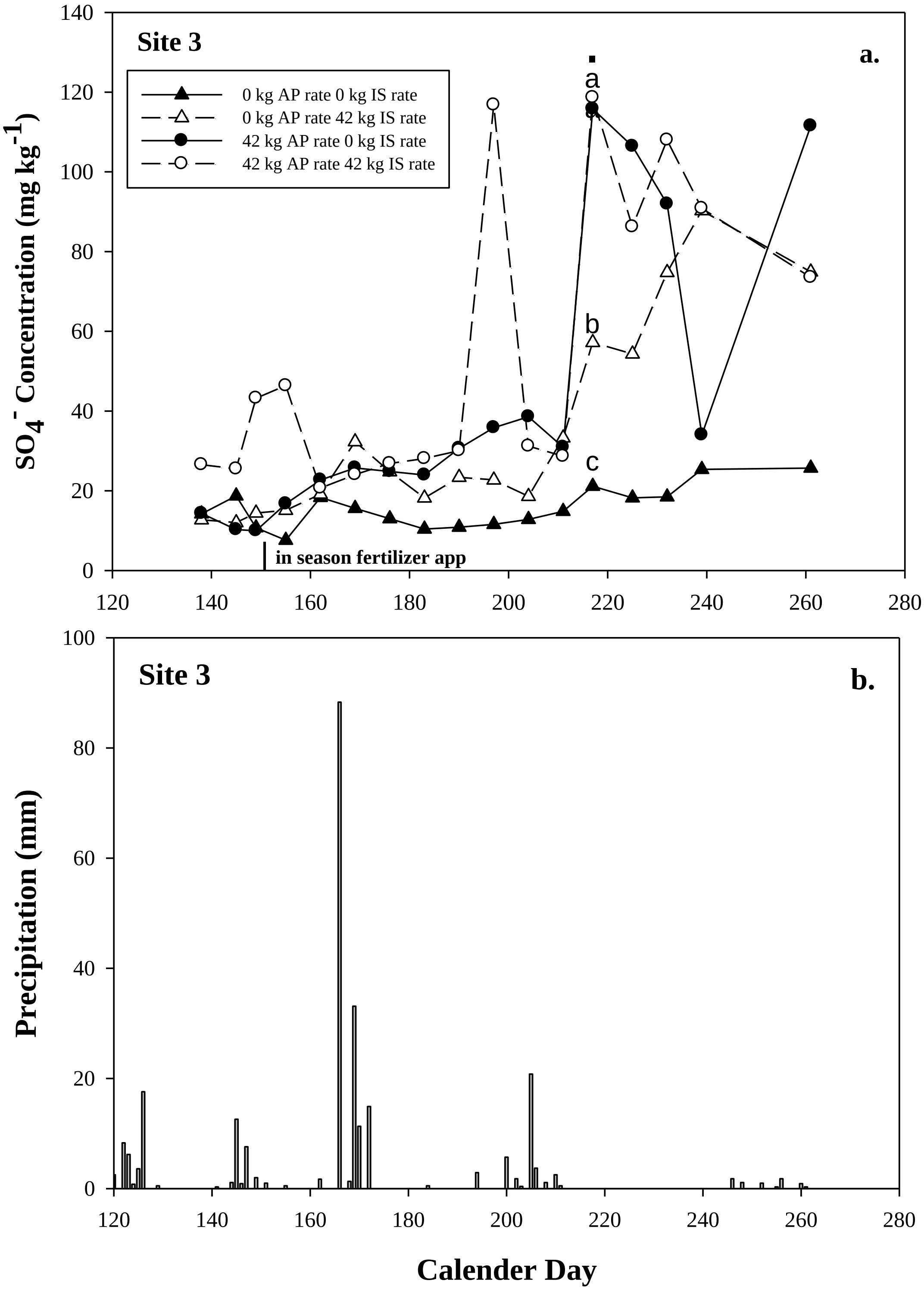


Figure 4. Soil pore water SO_4^{2-}-S concentration (a) for rates of 0 or 42 kg S ha^{-1} applied at planting (AP) in combination with 0 or 42 kg S ha^{-1} applied in-season (IS) and daily precipitation data (b) at Site 4. Letters indicate treatment significance within individual sampling dates.

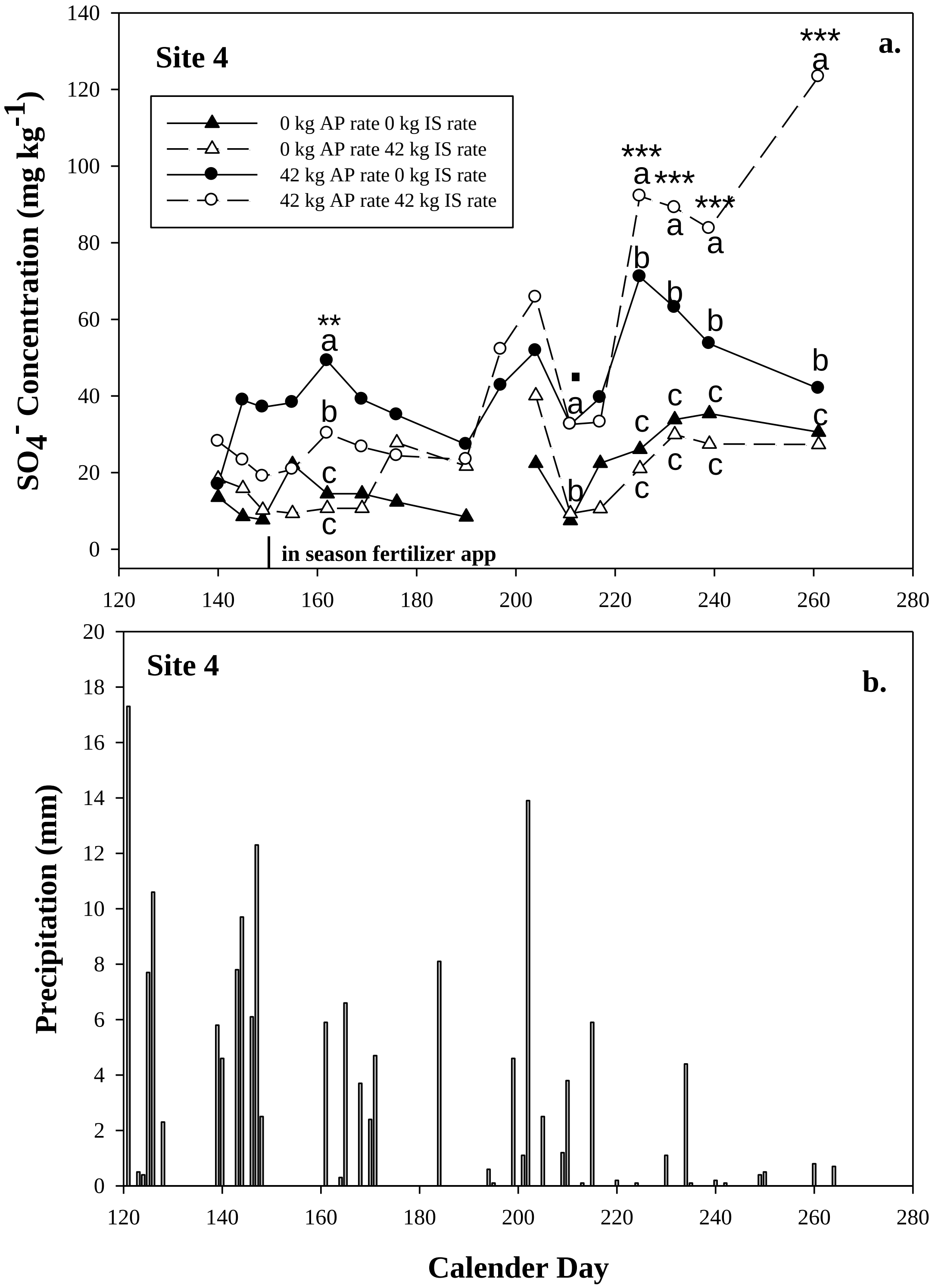


Figure 5. Relationship between ammonium acetate extractable soil K testing on field moist versus air dried soils from four locations.

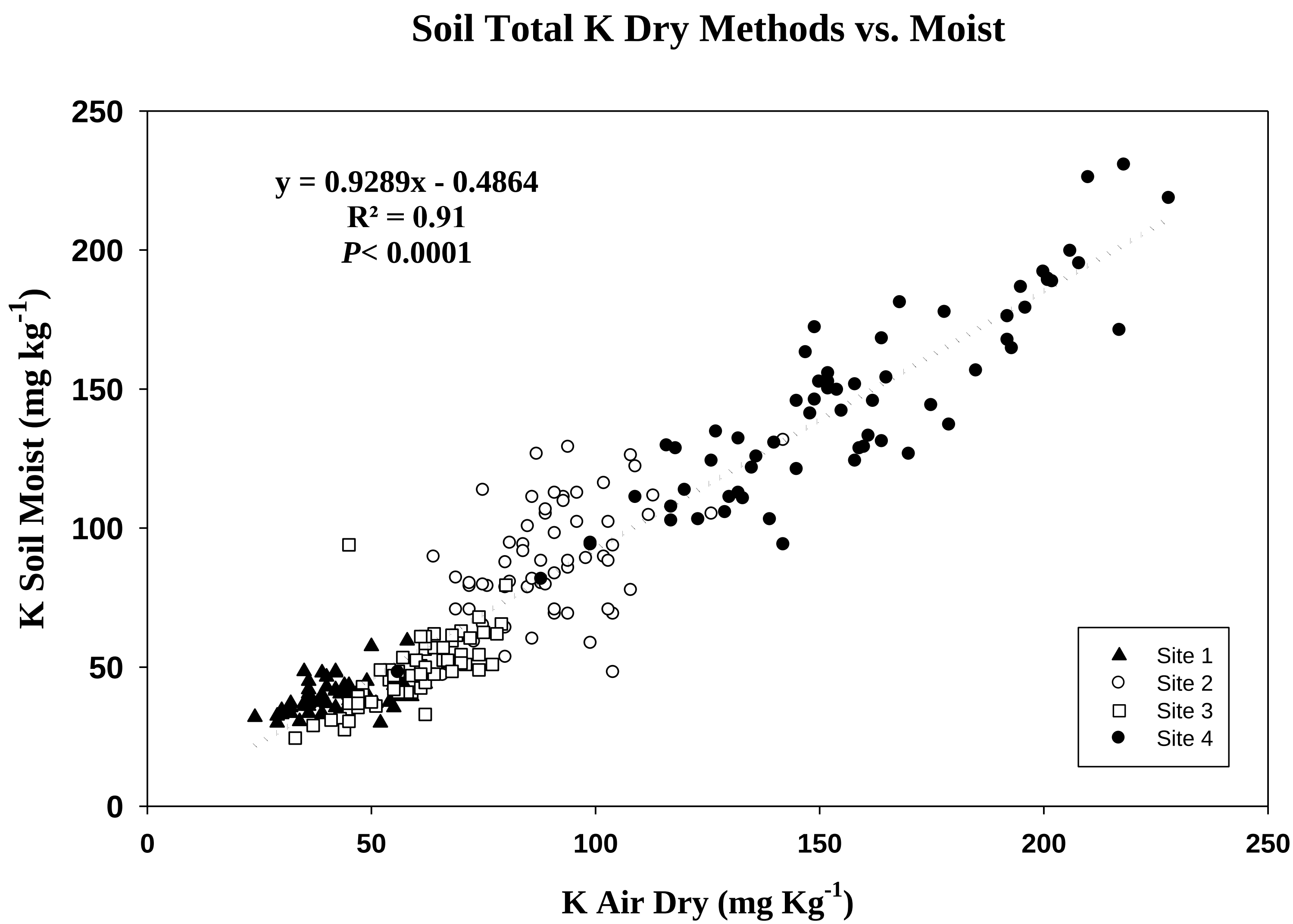


Figure 6. Relationship between average NDVI readings taken with the Greenseeker model 505 at V5-8 and V5-8 plant mass across potassium study locations.

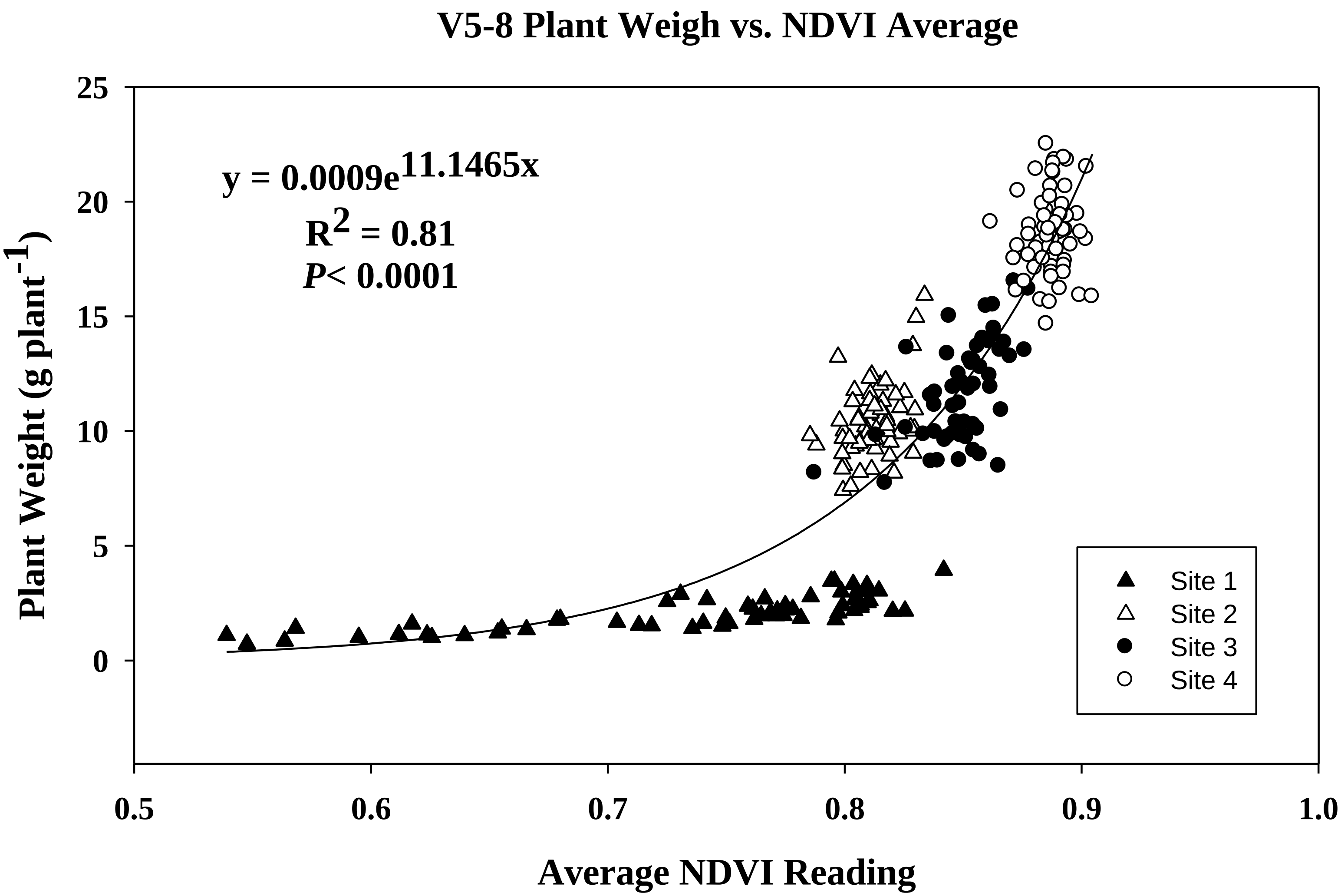


Figure 7. Soil pore water K concentration (a) for rates of 0 or 215 kg K ha^{-1} applied at planting (AP) in combination with 0 or 215 kg K ha^{-1} applied in-season (IS) and daily precipitation data (b) at Site 1. Letters indicate treatment significance within individual sampling dates.

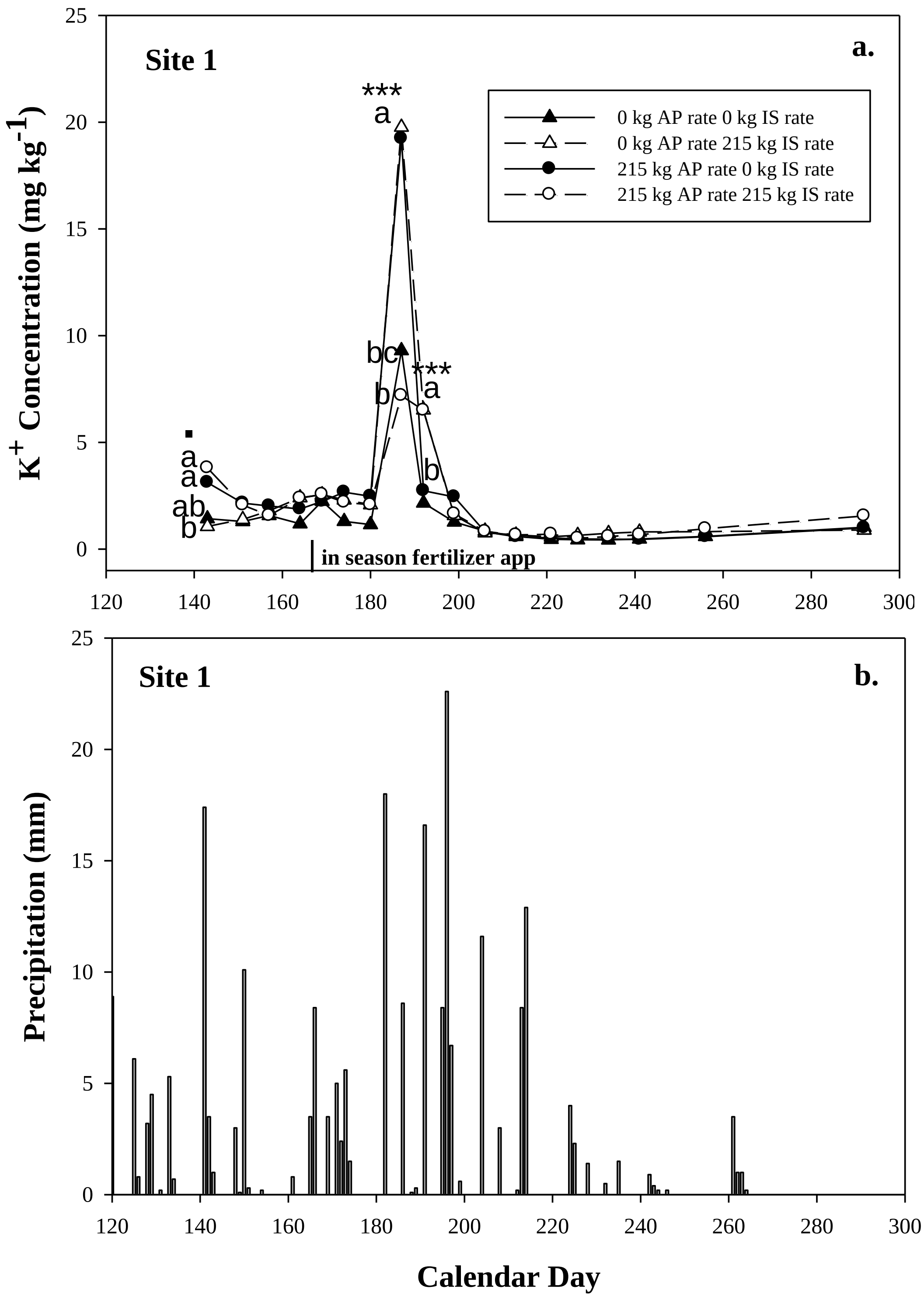


Figure 8. Soil pore water K concentration (a) for rates of 0 or 215 kg K ha^{-1} applied at planting (AP) in combination with 0 or 215 kg K ha^{-1} applied in-season (IS) and daily precipitation data (b) at Site 2. Letters indicate treatment significance within individual sampling dates.

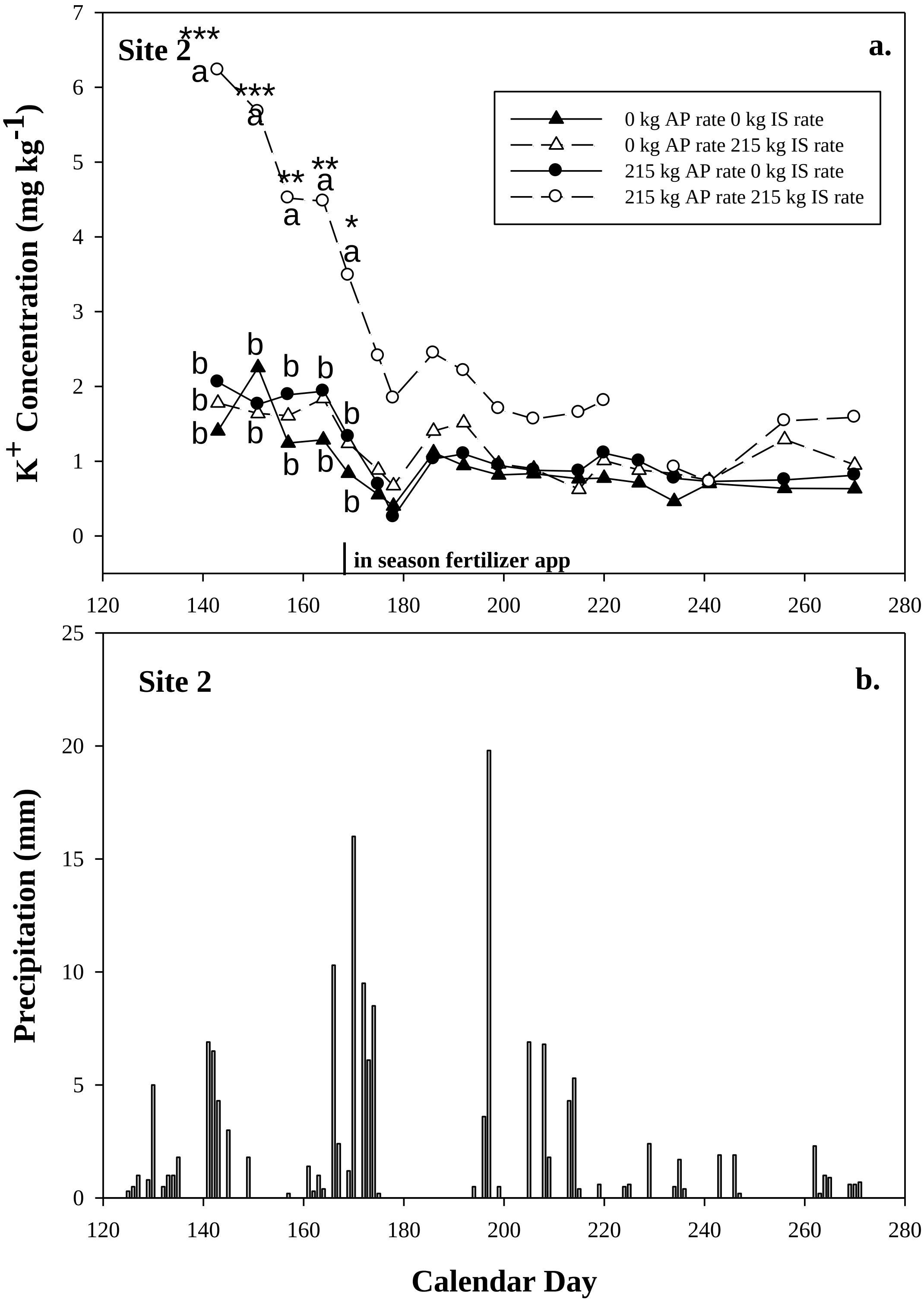


Figure 9. Soil pore water K concentration (a) for rates of 0 or 215 kg K ha^{-1} applied at planting (AP) in combination with 0 or 215 kg K ha^{-1} applied in-season (IS) and daily precipitation data (b) at Site 3. Letters indicate treatment significance within individual sampling dates.

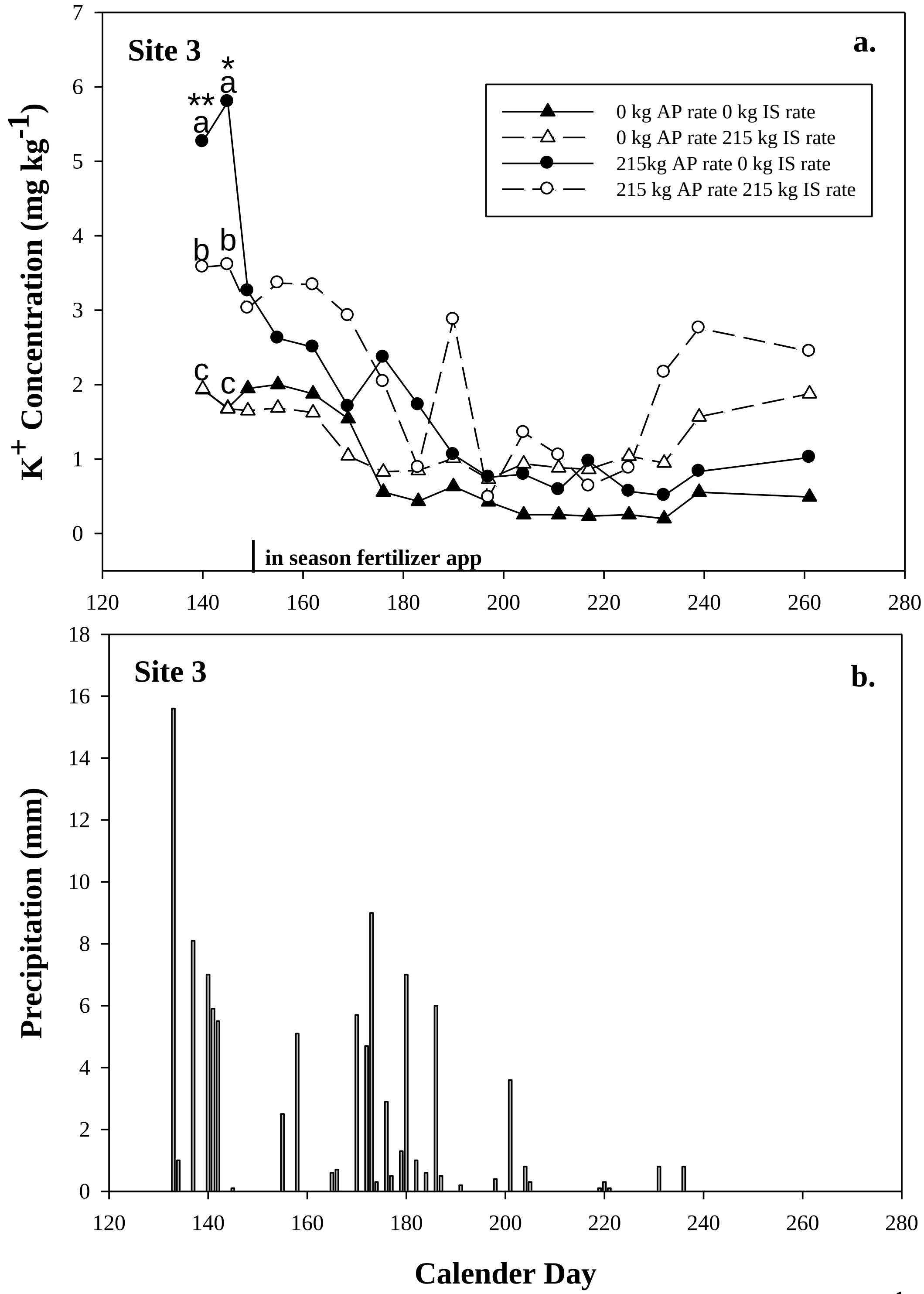
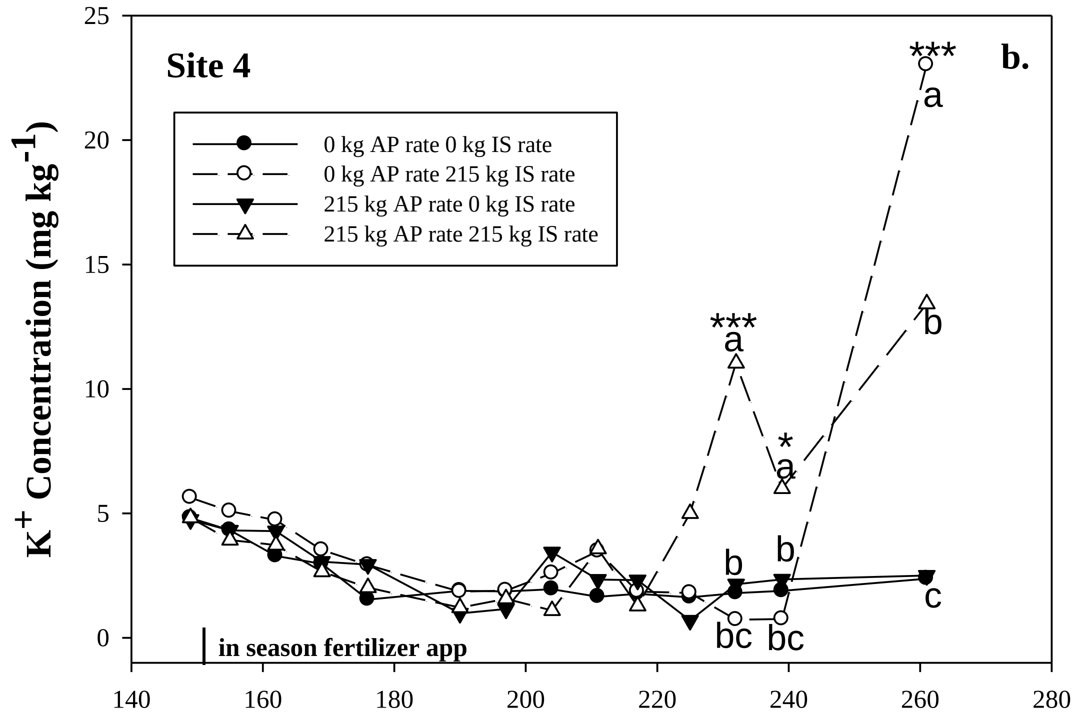
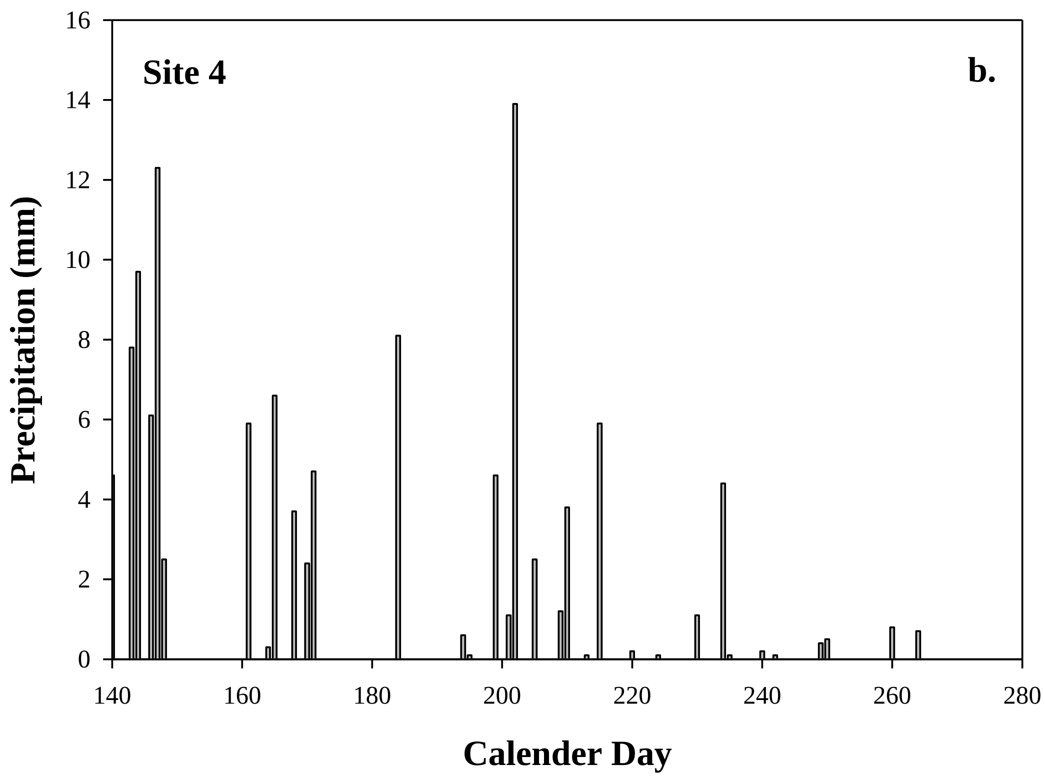


Figure 10. Soil pore water K concentration (a) for rates of 0 or 215 kg K ha^{-1} applied at planting (AP) in combination with 0 or 215 kg K ha^{-1} applied in-season (IS) and

daily precipitation data (b) at Site 4. Letters indicate treatment significance within individual sampling dates.





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